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Bulletin 57
(Part 1 of 4 Parts)

THE SHOCK AND VIBRATION BULLETIN

Part 1
**Welcome, Keynote Address,
Invited Papers, Nondevelopment
Items Workshop, and
Pyrotechnic Shock Workshop
(From 56th Shock and Vibration
Symposium)**

JANUARY 1987

A Publication of
THE SHOCK AND VIBRATION
INFORMATION CENTER
Naval Research Laboratory, Washington, D.C.

Office of
The Under Secretary of Defense
for Research and Engineering

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The 57th Symposium on Shock and Vibration was held in New Orleans, Louisiana, October 14-16, 1986. The Defense Nuclear Agency, Washington, DC and the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi were the hosts.

Office of
The Under Secretary of Defense
for Research and Engineering

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Tuesday 14 October, A.M.	Opening Session	Dr. Don A. Linger, Defense Nuclear Agency, Washington, DC	Dr. Sam Kiger, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS
Tuesday 14 October, P.M.	Instrumentation	Mr. Richard P. Joyce, IIT Research Institute, Chicago, IL	Mr. W. Scott Walton U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, MD
Tuesday 14 October, P.M.	Shock Analysis	Mr. James D. Cooper, Defense Nuclear Agency, Washington, DC	Mr. William J. Flathau, JAYCOR, Vicksburg, MS
Wednesday 15 October, A.M.	Plenary A	Rudolph H. Volin, P.E., Shock and Vibration Information Center, Naval Research Laboratory, Washington, DC	
Wednesday 15 October, A.M.	Nondevelopment Items Workshop, Session I, Methods	Mr. James W. Daniel, U.S. Army Missile Command, Redstone Arsenal, AL	Mr. Paul Hahn, Martin Marietta Orlando Aerospace, Orlando, FL
Wednesday 15 October, A.M.	Structural Dynamics I	Mr. Stanley Barrett, Martin Marietta Denver Aerospace, Denver, CO	Mr. W. Paul Dunn, The Aerospace Corporation, El Segundo, CA
Wednesday 15 October, A.M.	Isolation and Damping	Dr. Paul N. Sonnenburg, Physicon, Inc., Huntsville, AL	Matthew Kluesener, P.E., University of Dayton Research Institute, Dayton, OH
Wednesday 15 October, P.M.	Nondevelopment Items Workshop, Session II, Case Histories	Mr. Howard Camp, Jr., U.S. Army Communications-Electronics Command, Ft. Monmouth, NJ	Edgar K. Stewart, P.E., U.S. Army Armament Command, Dover NJ
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Wednesday 15 October, P.M.	Shock Testing	Mr. David Coltharp, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS	Mr. Steve Tanner, Naval Weapons Center, China Lake, CA
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WELCOME

WELCOME

Robert W. Whalin, PhD, P.E.
Technical Director
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

On behalf of the U.S. Army Engineer Waterways Experiment Station (WES), it is my sincere pleasure to welcome each of you to this 57th Shock and Vibration Symposium. The WES laboratory complex, located in Vicksburg, Mississippi, is the principal research and development facility of the Corps of Engineers. In lieu of an actual tour of WES, I will give you a brief slide tour of each of the six laboratories that make up WES, along with a closer look at a few selected WES research programs that I think you will find particularly interesting.

The Hydraulics Laboratory uses physical models, full-scale field data, and numerical models to investigate locks and dams, flood-control structures, river and harbor construction projects, sedimentation, erosion, and water quality. Our Geotechnical Laboratory is involved in research in areas of soil and rock mechanics, engineering geology and geophysics, pavements, earthquake engineering, structural foundation design, and vehicle mobility and trafficability.

Research programs in the Structures Laboratory (SL) include weapons effects, earth dynamics, structural behavior, and construction materials. SL engineers design and analyze structures to resist blast and earthquake loadings, define the effects of explosive events, evaluate construction materials in service, and study stresses in soil and rock masses, especially as associated with transient loadings.

The Environmental Laboratory research centers on dredged material-related studies, wetlands, hazardous waste, stand-off mine detection, fixed installation camouflage, automatic target recognition, and military hydrology. The Coastal Engineering Research Center (CERC) is the nation's center of excellence in coastal engineering and performs research and development investigations concerning shore and beach erosion control, storm protection, sand bypassing, dredging, breakwaters, jetties, navigation channel design and maintenance, wave climatology and hurricane surges.

The newly created Information Technology Laboratory (ITL) develops and evaluates computer hardware and software systems and packages for engineering purposes. WES technology transfer via technical publications and other means is another effort conducted by the ITL.

I have selected four current WES research programs for a little closer look; high-velocity projectile impact and penetration, missile silo basing concepts, nuclear weapons effects simulation techniques, and transducers to measure very high-pressure, high-shock, environments. Each of these programs are of interest to the research community here today, and they each represent research areas where important advances in the state of the art have been made in recent years.

High-Velocity Projectile Impact and Penetration:

With the increase in accuracy of both conventional and nuclear weapons, and the increasing hardness of protective structures, the subsurface burst is becoming a more attractive option for target kill. Also, protective layers can be designed to defeat "smart bombs" with penetrating capability.

The main thrust of WES's research and development in this area is to develop mathematical models and associated computer software for describing the interaction of the projectile with the target. Experimental verification of the models is usually carried out using both subscale and full-scale test results. Figure 1 shows a typical numerical simulation of the penetration of a long length-to-diameter projectile into a simulated rock-rubble matrix at an impact velocity of 1,000 ft/s. These calculations are carried out with a discrete-element computer program that allows for the movement and/or fracturing of individual blocks. Figure 2 shows the predicted structural dynamic response of the projectile during the first msec of penetration into the simulated rock rubble. These calculations are conducted with finite-element computer codes using loads from the discrete-element codes as input. The purpose of these calculations is to configure optimum rock-rubble/boulder screens for defeating air-delivered projectiles. Figure 3 shows an experimental setup consisting of a sled track and a rock-rubble target for verification of the numerical calculations. The projectile will be propelled by the attached rockets to reach the desired velocity at the time of impact. More recently, WES has been conducting studies in shielding methodology for protecting buried or semiburied military installations against incoming weapons. The use of rock-rubble/boulder screens as a candidate protective overlay has been investigated, and design procedures have been developed for their use in protective design.

Missile Silo Basing Concepts:

For the past 4 years, WES has conducted hardened silo research in support of the Air Force Ballistic Missile Office. The Hard Silo Component Test Program, an outgrowth of recommendations from the President's commission on strategic forces, was designed to develop hardening techniques for, first, the Small Missile System; and, currently, for the Peacekeeper Missile System. WES has conducted over 100 component tests to evaluate various silo designs. Figure 4 shows the type of component tests we have conducted in the last year to support this program. Although exact numbers are classified, I can tell you that the state of the art has progressed in just a few years from the capability of building silos to withstand, at best, a few thousand psi to current silo designs that have successfully withstood simulated peak overpressures of many tens of thousands of psi. This rapidly advancing technology has developed as a result of our better understanding of the behavior of confined concrete. Figure 5 shows the typical steel layout in a hard silo component. These rapid advances in structural designs have required parallel advances in our ability to simulate and measure the extremely high-pressure, high-shock, environment associated with a nearby nuclear event.

Simulation Development:

Peak overpressure of tens of thousands of psi can occur at ranges which are within accuracy of current weapon systems. At these close ranges, pressure gradients are extremely steep, and there are many crater- and direct-induced, as well as airblast-induced, shock effects that must be simulated to evaluate the survival of a test structure. Figure 6 shows the configuration of a crater and related effects simulation (CARES). The CARES can provide an accurate simulation of all of these effects. Computer codes to calculate these effects, as well as procedures using high explosives to simulate them, have improved significantly in the past few years.

Transducer Development:

As the severity of the blast environments increased, new transducers to document the environment had to be developed. In saturated soils under explosive loading conditions, ground shocks are created which are characterized by extremely high acceleration, but finite velocities. In order to measure these velocities, a transducer must survive in the associated high-acceleration environment. A family of transducers has been developed at WES that employs commercial, high-range accelerometers on miniature diaphragms (Figure 7). These transducers, known as shock-isolated accelerometers, can successfully operate in a shock environment whose lower bound is 100,000 g's, and, theoretically, can measure velocities in shock environments of virtually infinite accelerations. Work is currently underway to extend their upper velocity range of 120 ft/s to over 300 ft/s.

Several papers related to these research programs will be presented here at the symposium during the next 3 days. These papers will provide many of the interesting details that I have had to leave out. I urge you to attend as many presentations as you can, to ask questions, to participate. The success of the Symposium depends upon the active participation of each of us. I look forward to an interesting and successful symposium and, again, WELCOME.

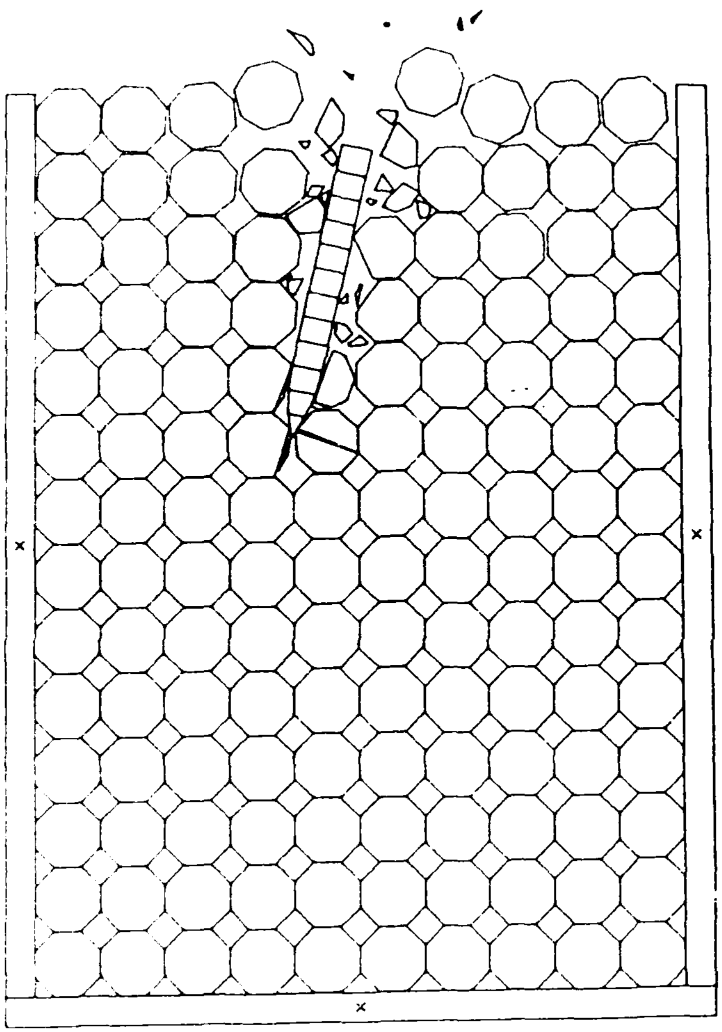


Figure 1. Field plot of projectile-boulder screen at t = 9 msec (Reference 1).

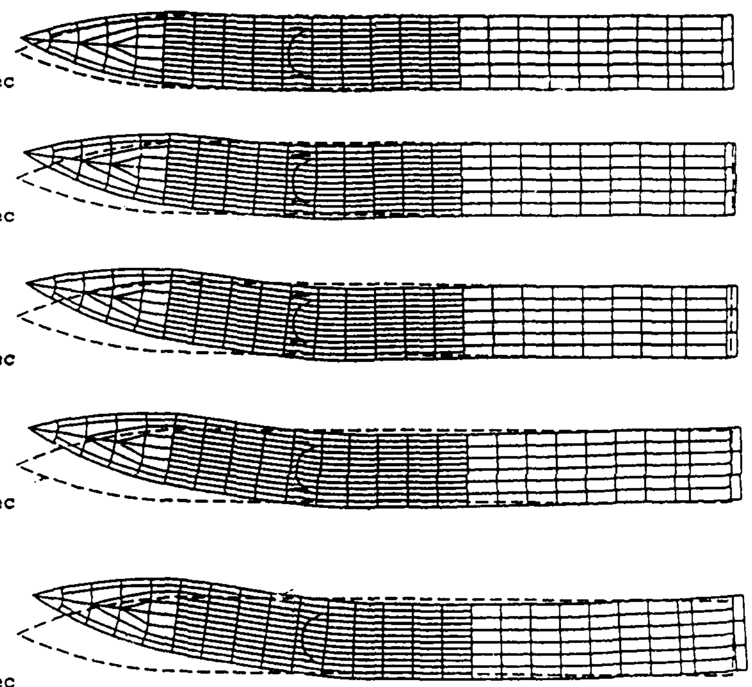


Figure 2. Structural response of projectile during the first msec of penetration into boulder screen (Reference 1).

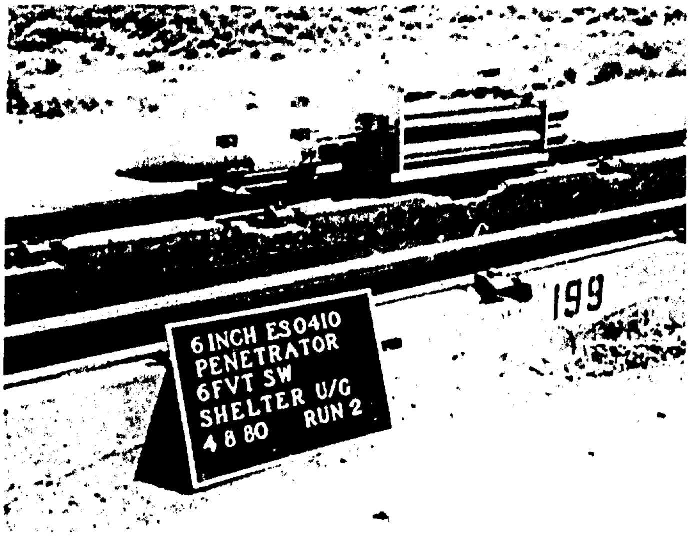


Figure 3. Projectile loaded on track prior to firing into boulder screen.

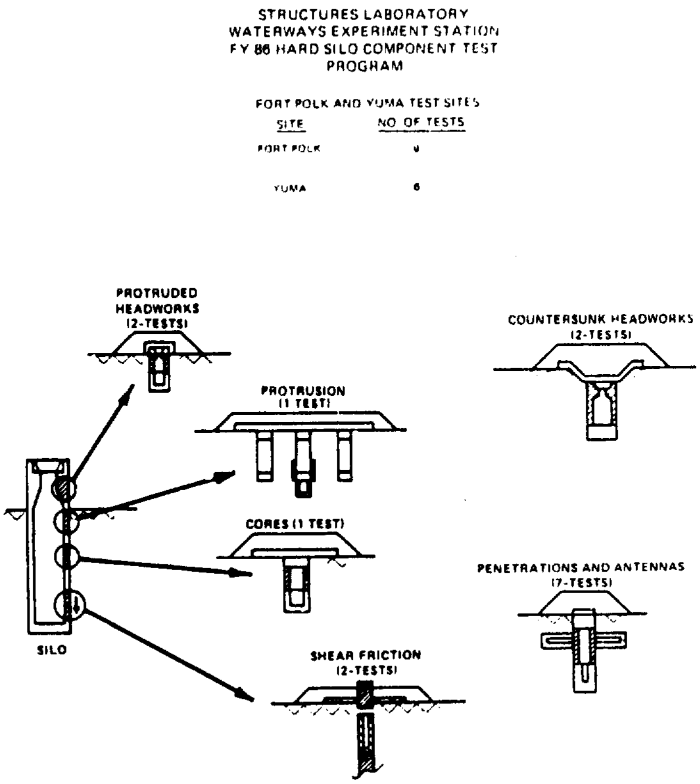


Figure 4. Summary of FY86 Hard Silo Component Tests.

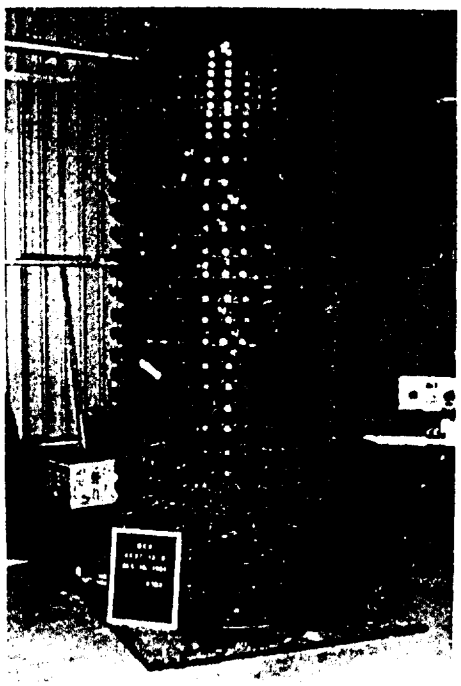


Figure 5. Typical reinforcement for Hard Silo Component structures.

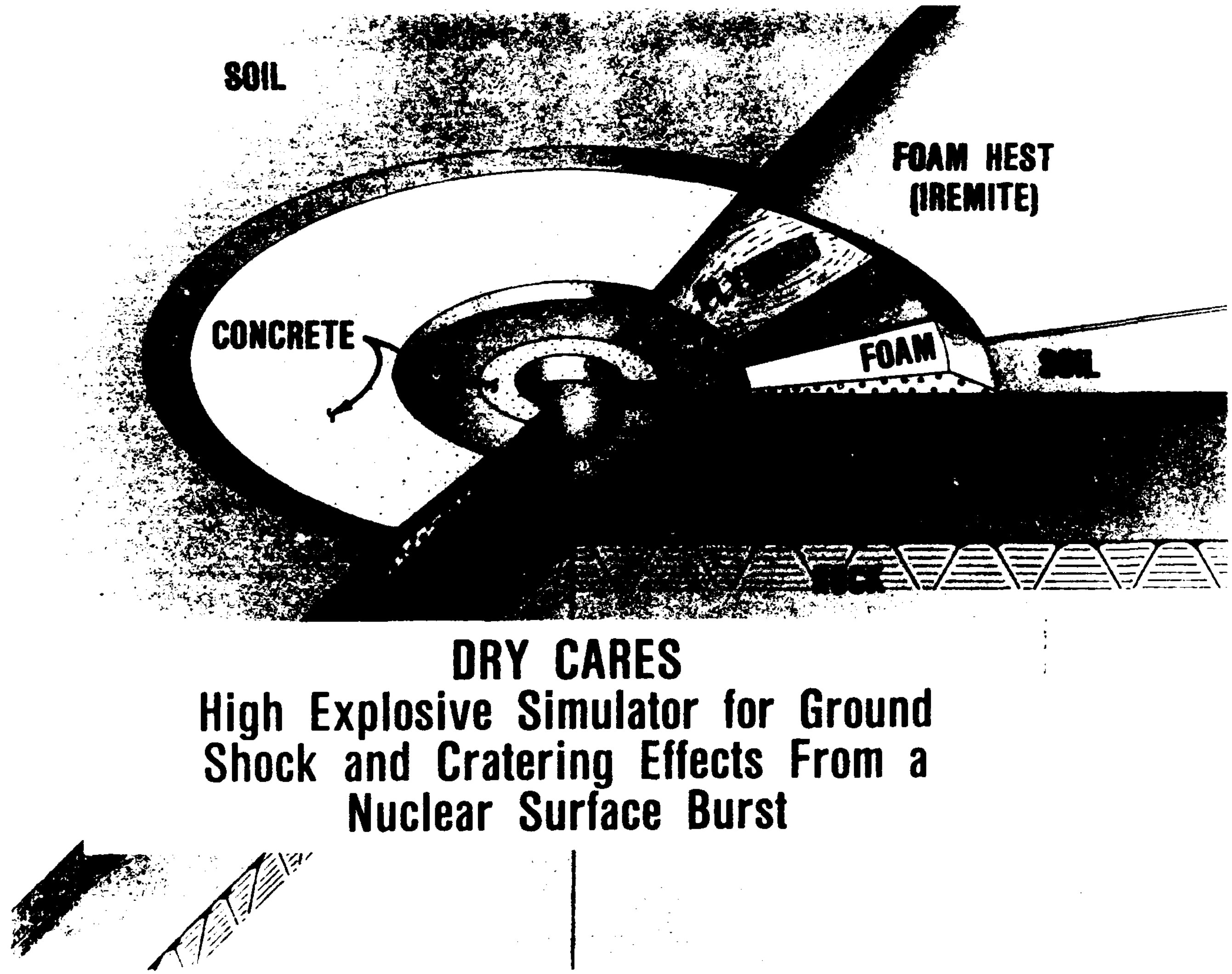


Figure 6. Configuration of Crater and Related Effects Simulation (CARES).

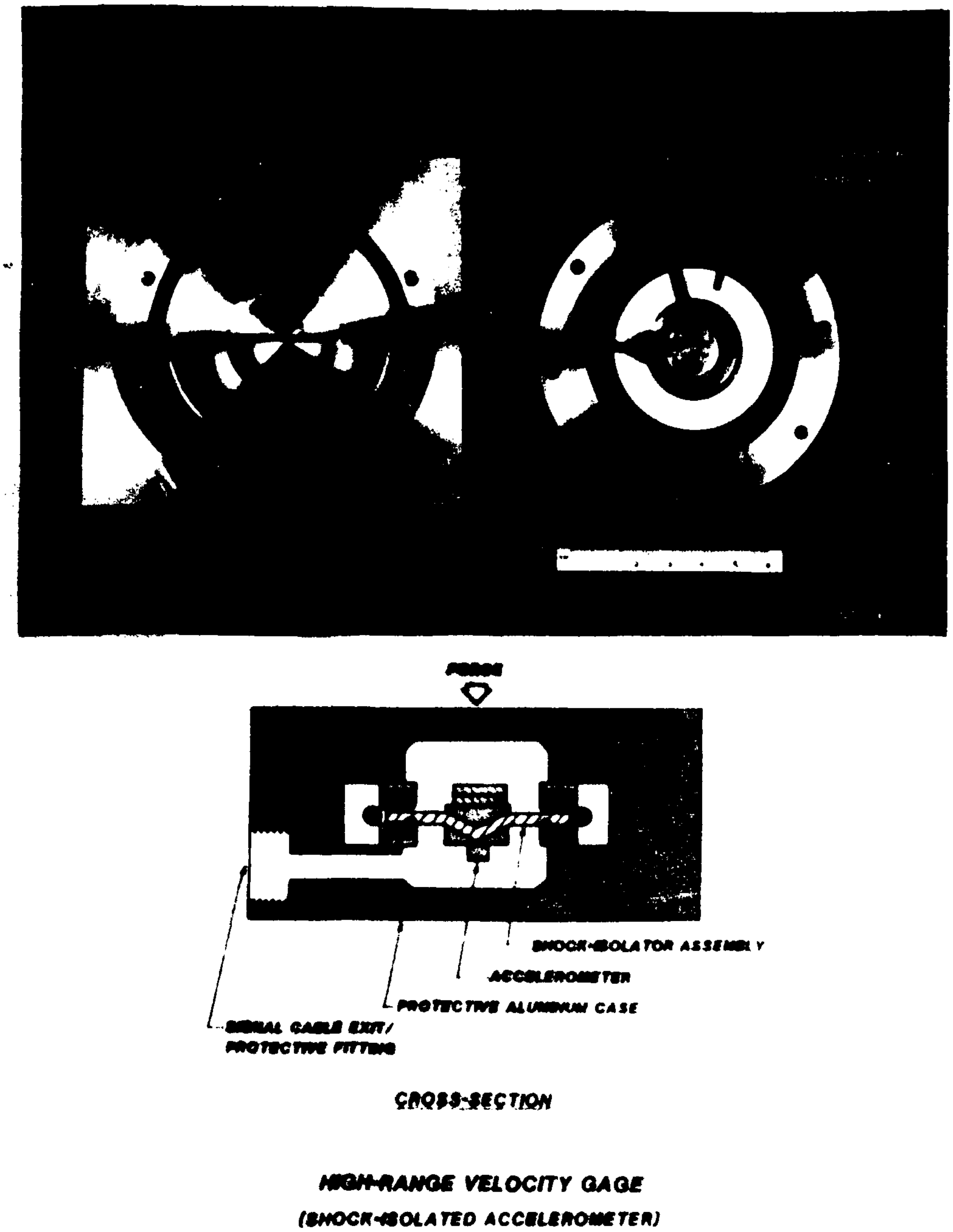


Figure 7. High-range velocity gage (Shock Isolated Accelerometer).

KEYNOTE ADDRESS

KEYNOTE ADDRESS

ICBM Modernization: A Shock and Vibration Perspective

Eugene Sevin

Assistant Deputy Under Secretary (Offensive & Space Systems)
Office of the Under Secretary of Defense Research & Engineering

(Keynote Speech delivered to the 57th Shock & Vibration Symposium, October 13-16, 1986; New Orleans, LA)

It is an honor and great pleasure for me to be with you at the 57th Shock and Vibration symposium and celebrating the 40th anniversary of SVIC. Those of you who thought the symposium an annual event might want to work out the sequence for holding 57 symposia in 40 years. Of considerably greater importance to all of us, however, is whether we will be together next year to celebrate the 41st year/58th symposium. As I am sure all of you know, the Navy no longer intends to sponsor the SVIC and has recommended disestablishing it as a DoD Information Analysis Center. The Center's Technical Advisory Group will be meeting this week at the symposium to consider ways in which SVIC and/or its principal functions; the symposium, Bulletin, Digest, monographs, etc. can be continued for the benefit of the shock and vibration community. If there is to be a 41st anniversary then I think it absolutely essential that the voice of our technical community make itself heard.

I know that many of us here today would acknowledge the importance of the professional services and opportunities SVIC has meant for our own careers. I first presented a paper at the 1960 Symposium and I have participated in most of the symposia since. Walt Pilkey and I co-authored one of the SVIC monographs; Walt, Ron Eshelman and I, all of us then at IITRI, together with Bill Mutch and Henry Pusey at SVIC, started up the Shock and Vibration Digest. Thus, I personally have a lot at stake in SVIC, and as I look through the program for this symposium and at this audience, I know that many of you must feel similarly. Particularly important has been the professional forum SVIC has provided for the nuclear effects and hardening community, meeting a vital need for peer association and publication of classified research. Please take the opportunity during the course of the symposium to make your views known to the SVIC staff and the TAG members regarding the importance of the Center.

I've selected for my topic today "ICBM Modernization: A Shock & Vibration Perspective". I confess that ICBM modernization is about all I have on my mind these days; were I to be addressing the Society of Agricultural Engineers, my topic doubtless would be "ICBM Modernization: An Agricultural Perspective". I'm hard put to think of another topic of such national security import, technical accomplishment and engineering challenge that at the same time is so politically complicated. Now, while I most definitely will not be speaking on "ICBM Modernization: A Political Perspective", there is in all of this a fascinating interrelationship between political and technological imperatives. Let me begin with this theme.

Modernization of the land-based ICBM leg of the strategic triad began 10 years ago with the development of the MX missile, a large SALT compatible ICBM whose primary justification was to correct the perceived vulnerability of silo-based Minuteman to the steadily increasing accuracy of new Soviet ICBMs. The missile development has been extremely successful; indeed, a piece of cake compared to finding a survivable and politically acceptable way of basing it. Now, 10 years later ICBM modernization remains the centerpiece of the Reagan Administration's plans for Strategic Force modernization, i.e., improvements to all three legs of our strategic triad: submarine launched ballistic missiles, strategic bombers and the land-based ICBMs.

The President's program was announced in late 1981 when he rejected the Carter Administration (and Congressionally approved) plan for deceptively basing MX in modestly hardened shelters and challenged DoD to come up with a better idea. The following May the keynote speaker at the 52nd Symposium (held in this very auditorium) described the three options for long-term basing of MX then under consideration: Deep underground basing, continuous airborne patrol aircraft and ballistic missile defense of land-based shelters.

The speaker also said that "This plan . . . will directly affect many of the people in this Symposium because they will be doing important work which is vital in bringing this plan to fruition." Well, I must tell you that a funny thing happened to MX on the way to Fruition, since the master plan today is largely "none of the above". Instead, 50 Peacekeepers (nee MX) are being installed in Minuteman silos (no more survivable than the Minutemen they replace), superhard silos, a garrisoned rail system, and several deceptive basing schemes are under consideration for deploying a second 50 Peacekeepers and the Air Force is developing aggressively a new, legislatively spec-ed, small ICBM that first entered the competition in 1983. Therefore, on behalf of the last keynote speaker at a SVIC symposium in New Orleans, I want to thank you for the splendid work you've done in helping ICBM Modernization along on its way to fruition.

What did happen, in fact, was a consequence of political difficulties the Administration's program faced in Congress and the solution crafted by the President's Commission on Strategic Forces, the Scowcroft Commission - a masterful blend of political astuteness and technological wishful thinking. The Scowcroft Commission recommended the deployment of 100 Peacekeeper missiles in existing Minuteman silos (for military effectiveness), the development of a Small ICBM (SICBM) that could be made mobile for survivability, continued research on superhard silo technology as a possible long-term survivable basing mode for Peacekeeper and/or the SICBM, and aggressive pursuit of strategic arms control. That's pretty much the program the Air Force has been following the past three years.

Let's examine the SICBM. The idea of a small, single warhead missile has been around for some time, but has never fared well in cost comparison with a large MIRVed missile on a per warhead basis. Mobility as a means of survivability has not been a serious contender in the past because of concern over public acceptance of nuclear missiles roaming the countryside. And why must they roam the countryside? Well, because roadable vehicles as we know then are only a few psi hard against airblast, so that large deployment areas are required to survive a determined barrage-type attack.

However, the Scowcroft Commission was intrigued with a new technology idea; that a missile carrier could be blast hardened without sacrificing mobility to where a survivable system was possible on available DoD-owned land. Also, the Commission viewed a small single warhead missile as less lucrative a target than a 10-RV Peacekeeper, and consequently more stabilizing and supportive of arms control objectives. Congress' contribution was not long in coming; they legislated that the SICBM could not weigh more than 30,000 lb and linked Peacekeeper deployment in Minuteman silos to progress on the small missile. And so was born the SICBM.

Now what were the technical imperatives in all of this? First was the technical rationale for believing that a missile carrier could be hardened to 30 psi (or more) in order to reduce deployment area requirements. The concept is to seal off air flow beneath the vehicle so that the vertical airblast forces have a stabilizing effect against the horizontal forces which act to displace it. At the same time, the vehicle is aerodynamically shaped to minimize the horizontal blast forces. The principle is straightforward, but its practicality had never been demonstrated. Several years ago DNA conducted an experiment on bread box-size objects to test how effective sealing had to be. The results were encouraging for the ideal airblast loading obtained with high explosives. Enthusiasm was muted, however, by what was known then about "real" blast loading, the practical implications of which are shown in Fig. 1.

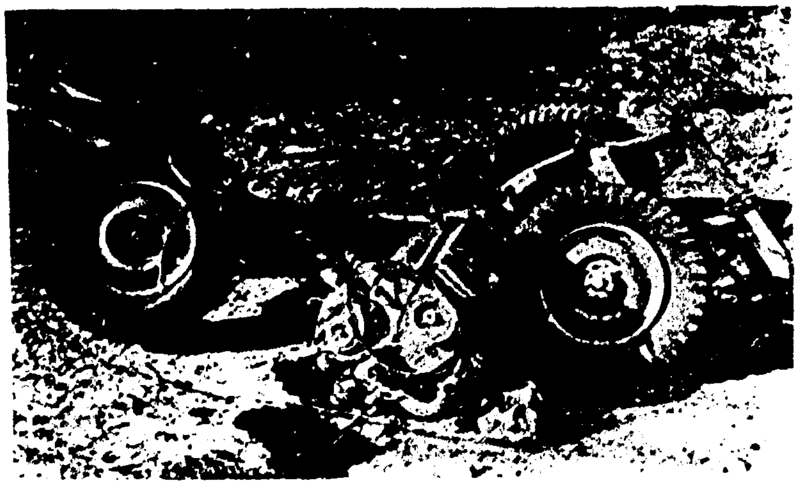
The jeep on the left was exposed to 10 psi from a low kiloton burst at the Pacific Proving Grounds. The water acts as a near ideal reflecting surface and the resulting airblast closely approximates an ideal Mach wave near the ground. Though turned over, the jeep was able to be driven away. The jeep on the right also saw 10 psi from about the same yield device but was demolished, as you can see. This test was conducted at the Nevada Test Site where fireball heating of the sandy lake bed surface increased the air shock loading on the jeep producing greatly increased loads and response. Little was known about this boundary layer phenomenon, or thermally precursed flow, at the time we undertook to develop a hardened mobile launcher (HML). During the past three years we have devoted a major effort to understand the underlying shock physics of thermally precursed flows, to develop methods for predicting the vehicle loads, and to devise reallistic testing techniques.

At the outset of the program the feasibility of the HML concept was unknown. Today it is a proven concept and a decision to proceed with full scale engineering development is expected in December. A one-fifth size proof-of-principle test was conducted last year. The energy source was nearly five kilotons of high explosive, corresponding to 8 kt nuclear equivalent. The simulation technique for thermally precursed flows is one of DNA's more remarkable inventions. More about this later.

Consider next silo basing. After the present Administration cancelled the Multiple Protective Structures (MPS) basing concept for MS and prior to adoption of the Scowcroft Commission plan, you may remember a short-lived scheme called Closely Spaced Basing, or Dense Pack. The problem with silo basing is the prospect that weapon accuracy will continue to improve to where a fixed target becomes vulnerable irrespective of how hard it is. The aggregate nuclear environment from a concentrated attack against closely spaced arrays of very hard silos was thought to be severe enough to preclude killing all of the silos in a prompt, single-wave attack. A multiple-wave attack requiring hours to complete was deemed implausible because of its complexity and the potential it allowed for counter attack between incoming waves. Unfortunately, there was something counter-intuitive about the Dense Pack concept; that individually vulnerable targets were survivable when placed close together.

Whatever the reason, Dense Pack went the way of its predecessors. However, the legacy of Dense Pack is with us today as the technology of Superhardening, with the prospect of silo-based missiles surviving to the very crater's edge. It is an interesting story of another technology challenge well met, with significant impact on our general understanding of nuclear weapon effects in the source region and our ability to simulate them by non-nuclear means.

Shot Lacrosse
~40 KT @ PPG
~3000' GR, SB
Jeeps Drivable



Shot Turk
~40 Kt @ NTS
~3000' GR
~200' SHOB
Jeeps Demolished

Fig. 1 — Nuclear Test Results

Hardened mobile launchers and superhard silos; different technology approaches at virtually opposite ends of the weapons effects spectrum - one too hard to destroy, the other too hard to find - and both posing challenging problems for the shock and vibration engineer. Interestingly enough there are currently other ICBM basing candidates at intermediate hardness levels that are not without their own technology challenges. Let's look briefly at these concepts before backtracking over the technology aspects and indicating how Shock and Vibration engineers can get us back on the road to fruition.

Besider frustrating an attacker through hardness or mobility, survivability can be achieved by deceptively basing the missile as well. One such approach would be to conceal a relatively small number of missiles among a much larger number of shelters, requiring an attack against all of the shelters to assure killing all of the missiles. Then presumably the attacker would be at a disadvantage provided that the marginal cost of the shelter does not exceed that of the attacking weapon. This was precisely the rationale of the MPS system advocated by the Carter Administration. From a survivability perspective, clearly, the critical issues have to do with the effectiveness of the security system employed to maintain the uncertainty in location of the missiles.

Concealment means not hiding where the missile is, but also where it is not. Considering the sophisticated means available for remote sensing of vibrational, seismic, acoustic and thermal signatures of the missile both in-transit and in-place, preservation of location uncertainty (PLU) over the long term is extremely challenging - and the greatest potential weakness of deceptive basing. With the MPS system this problem was exacerbated because of the large amount of land required to deploy over 4000 shelters at one mile intervals. This precluded imposing tight security around the entire deployment area, and security had to be restricted to a small area surrounding each shelter. This led to a requirement for a sophisticated missile simulator which, in turn, added appreciably to the cost of the shelter and missile transporter, and complicated operations greatly. In the end, the marginal cost advantage favored the attacker, which probably was a fatal flaw of the MPS concept along with environmental objections.

Currently, two other deceptive basing schemes are under study for Peacekeeper; one a version of the shallow tunnel - an earlier candidate for MX - and the other a new MPS-like concept known as Carry Hard. Carry Hard is a particularly good example of how technical innovation in hardening can change the very nature of the basing solution. Let me describe the Carry Hard idea briefly in relation to MPS. The MPS system employed a conventional approach to hardening in that each shelter was able to maintain, protect, and launch the missile; big ticket items such as the missile shock isolation and egress systems, as well as elements of the weapon control system, being included in every shelter, added substantially to the cost of the system. Cost considerations dictated only modest shelter hardening, but limiting shelter hardness turned out to have drastic implications for the MPS system in other respects, as was already noted.

In contrast, the Carry Hard shelters (silos) are very hard *when the missile is in place* but soft when empty. Moreover, virtually all launch support equipment (which was resident in the MPS shelters) is transported with the missile, including the shock isolation and egress mechanisms. Thus, Carry Hard realizes the benefits of a very hard aim point system (i.e., closer shelter spacing, less land for deployment, area security, easier concealment, etc.) without actually constructing expensively hardened aim points; instead, the hardness is carried with the missile, so to speak - hence, the name "Carry Hard".

Well, so far I've mentioned superhardness, mobile hardness, and now portable hardness - without saying much about how any of them work or what are the shock and vibration challenges. Let me spend the remainder of my time highlighting various aspects of superhard silos and hardened mobile launchers.

Superhard silos are intended to survive to within a football field length of a large yield nuclear surface burst - virtually to the crater's edge, where free-field environments are characterized by kilobars of surface pressure, many hundreds of g's acceleration, and meters of displacement, as well as intense electromagnetic, nuclear and thermal radiation. How is this possible? And how are we ever to prove it? The answer involves many considerations; a new appreciation of nuclear weapons effects, particularly airblast and cratering, beneficial siting geologies, improved understanding of steel-reinforced concrete under high strain rate loading, innovative silo subsystem designs - particularly shock isolation systems - and greatly improved dynamic test capabilities.

The silos are thick-walled cylinders, thermos bottle-like in cross section, and constructed of high-strength concrete with exceptionally heavy steel reinforcement, as depicted in Fig. 2. Now, the peak blast pressure acting on the silo headworks may exceed the compressive strength of the concrete by as much as a factor of 10; why doesn't the concrete crush up? Two properties of concrete come into play which account for a dramatic increase in compressive strength and ductility; strain rate and lateral confinement. Recent data demonstrate a doubling of the unconfined compressive strength of concrete under the high load rates of interest. Figure 3 illustrates the effect of lateral confinement on the stress-strain properties of concrete; above about 20% confinement, concrete is seen to resemble more a ductile metal than the brittle material it usually is thought to be. In application, the confinement is achieved through unconventionally large amounts of steel reinforcement in the radial and circumferential directions.

The time sequence of events associated with the initial high intensity compressive loading of the silo walls is illustrated in Fig. 4 based on detailed structural dynamics calculations for a point about midway along the silo wall. Note first the extremely rapid decay of the applied loading. Initially the concrete behaves as if in uniaxial compression, for which the confining ratio attains a theoretical value of 1/3 (for a Poisson ratio of 1/4). The effective compressive strength of the concrete probably exceeds 150 ksi at this time. The inertial confinement drops off as the wall begins to expand outward until the internal confining action of the reinforcing steel can be mobilized. Fortunately, it is during this time that the applied stress is itself most rapidly decaying. Subsequently, the soil stress wave arrives to apply an external confining pressure. Thus, we see that the effectively great strength of the silo wall depends critically on the ability of the reinforcing steel to mobilize internal confinement of the concrete.

The shock environment within the silo structure must be attenuated for the missile and launch-critical equipment to survive. Typically, the design problem is a tradeoff between limiting the accelerations transmitted to the missile by means of the shock isolation system (SIS) and the rattlespace provided in the silo - cost and complexity of a SIS against the cost of a larger silo.

Figure 5 portrays the general SIS design problem in a broader context as the packaging of a missile in a silo system. Rattlespace can be reduced without exceeding acceleration thresholds for the missile by means of a canister (or strongback) and through a horizontal and vertical SIS. In combination, these can approach in effectiveness an optimum SIS for the uncanisterized missile. Further reductions in rattlespace, however, would require additional shock hardening of the missile. The potential for combined canister and SIS design is being explored by DNA as part of their Advanced Silo Hardness program.

While the general approach to SIS design is well understood, application to superhard silos requires major improvements in both vertical and lateral isolation. Coil spring and liquid spring vertical isolators representative of Minuteman technology cannot handle current large stroke demands, and have given way to nylon rope assemblies utilizing optimally damped liquid or hydropneumatic springs.

The missile-canister-SIS-silo system can be further extended to include isolation of the silo itself. So-called External Shock Mitigation (ESM) techniques include energy absorbing material surrounding the silo or ground shock modifying arrangements located uprange of the silo. Several examples of ESM methods are shown in Fig. 6. While illustrating mitigation of horizontal ground

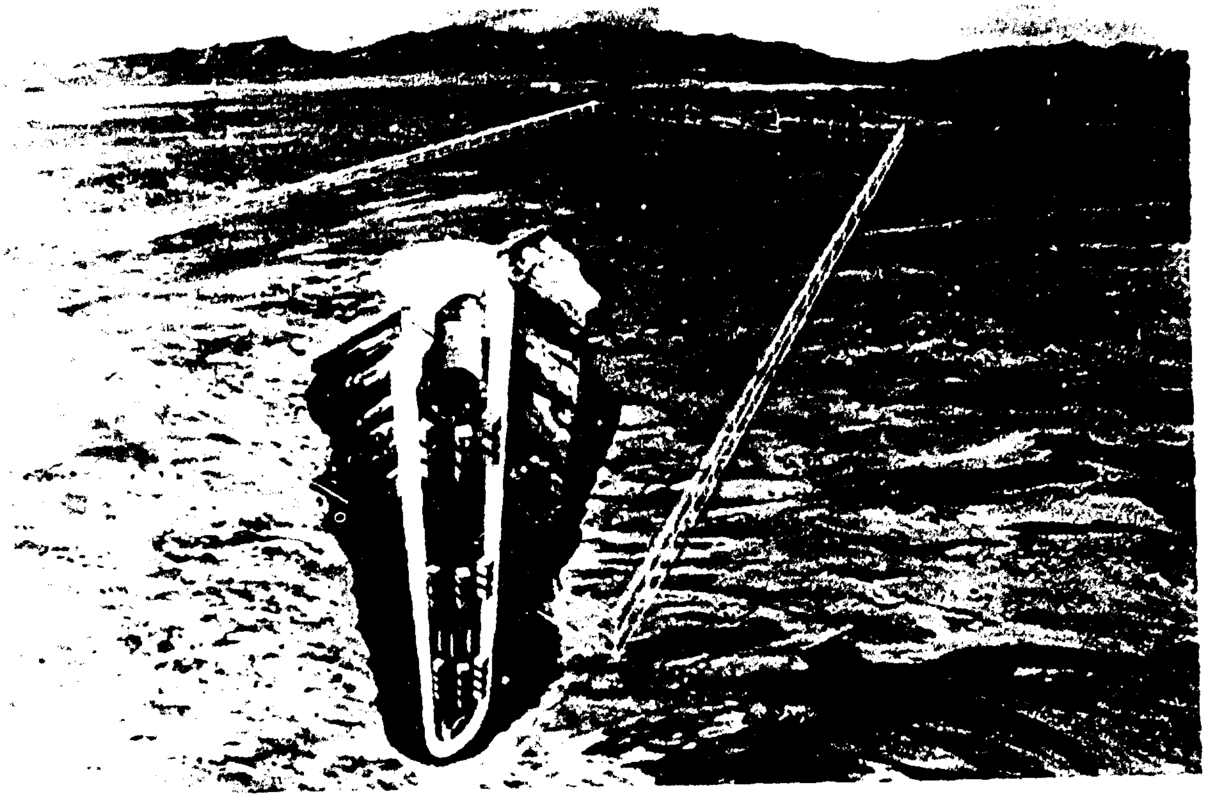


Fig. 2 — Superhard silo

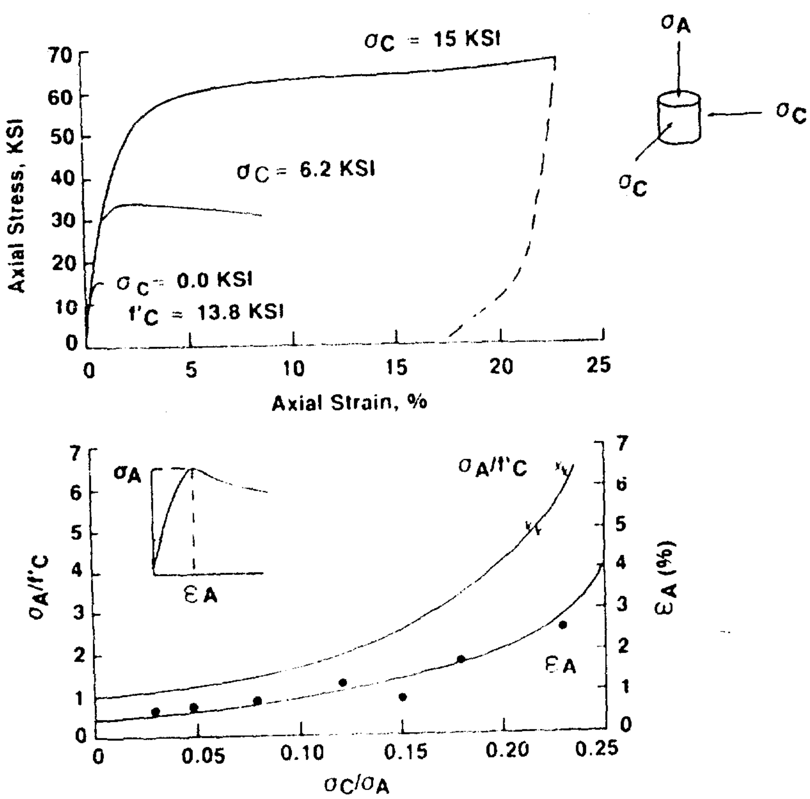


Fig. 3 — Stress-Strain curves for confined concrete

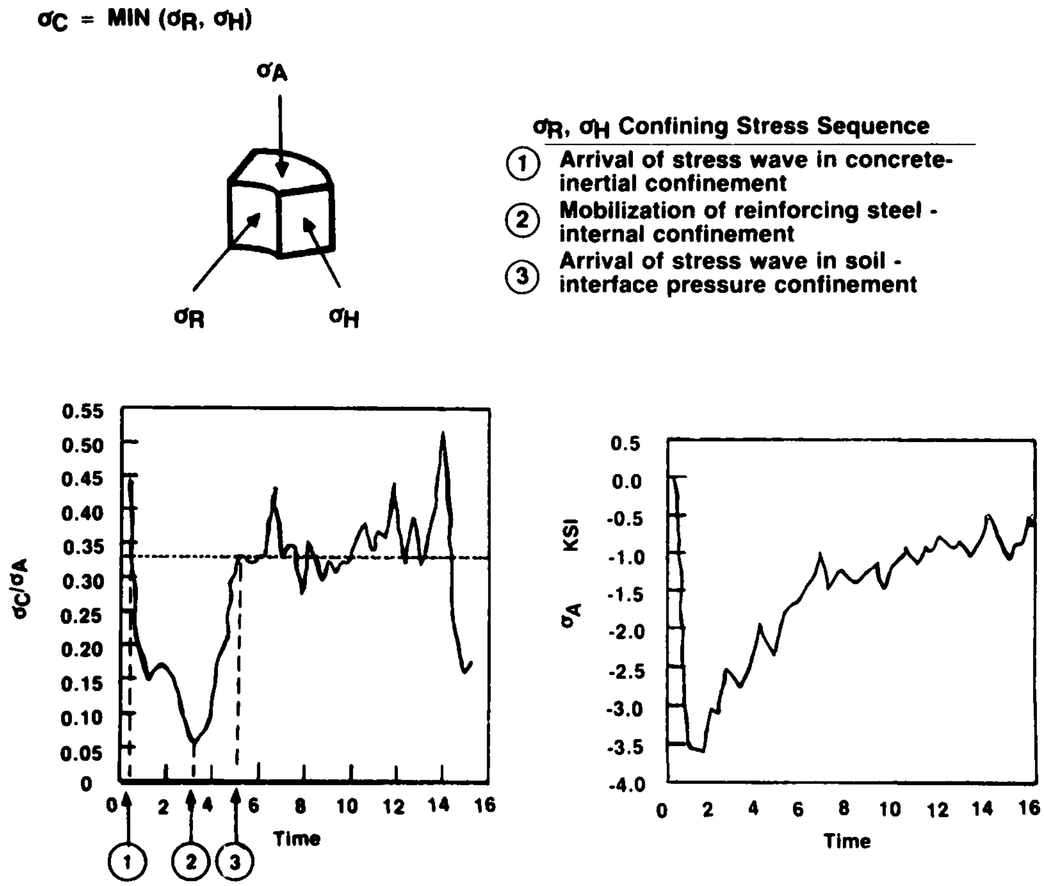


Fig. 4 — Time sequence of silo loading

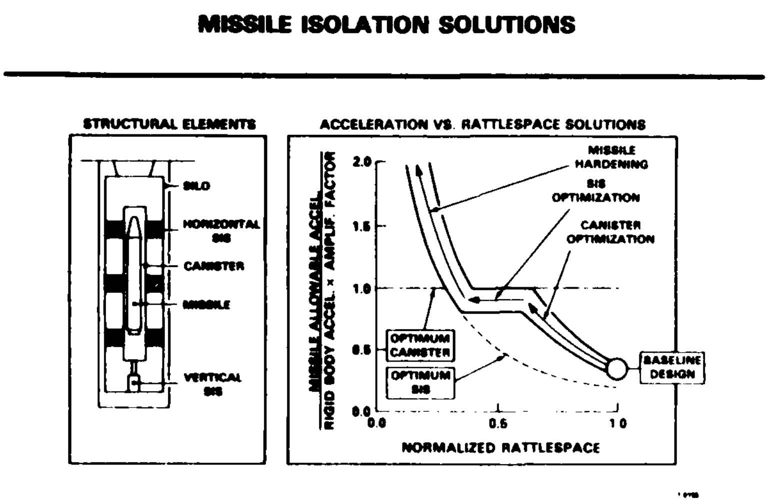


Fig. 5 — Missile isolation solutions

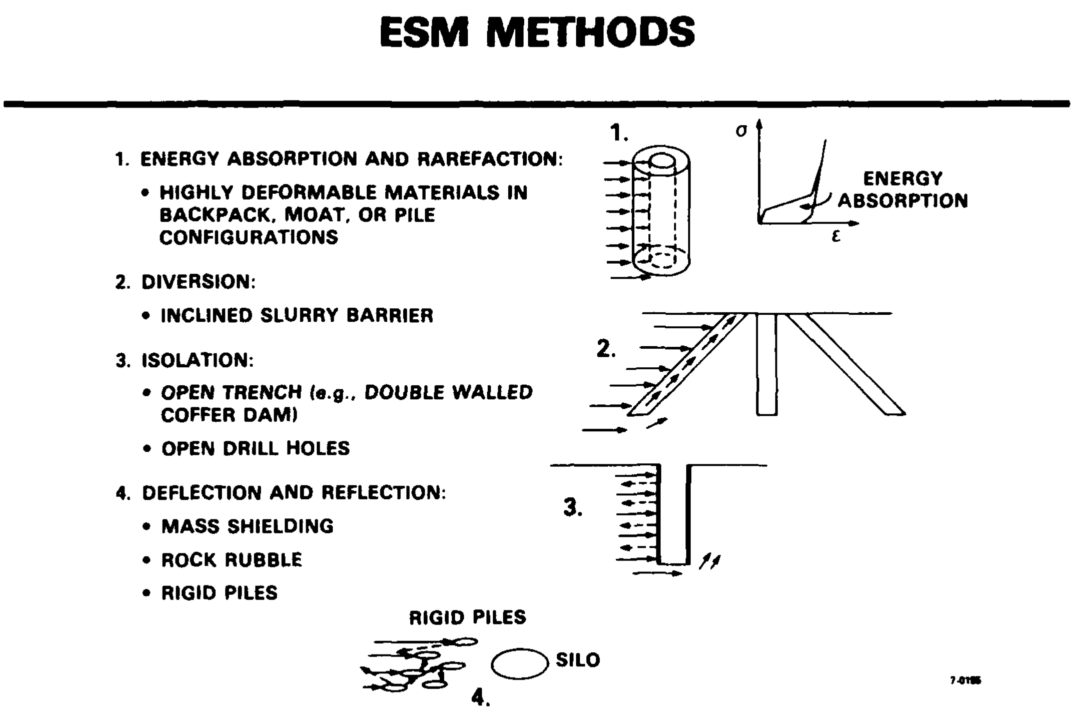


Fig. 6 — ESM methods

shock, certain of these techniques can be applied in the vertical direction as well. The potential for ESM is evident from the results in Fig. 7. The influence of crushable backfill surrounding the silo on the acceleration-rattlespace relationship is shown for an optimum SIS and specified free-field ground shock. Several interpretations are possible. A minimum rattlespace of 26 inches required for a 15g missile in a bare silo is reduced to 3 inches with the indicated ESM. Alternatively, 26 inch rattlespace might accommodate a less hard 3g missile with this particular ESM. Thus, the possible benefits of ESM are increased hardness or reduced rattlespace for a given hardness, and reduction in sensitivity of SIS response to threat and site specific uncertainties. While the concept shows promise theoretically, there is insufficient data as yet to support engineering implementation. DNA is pursuing ESM technology under its advanced silo hardness program.

Some years ago (at the 46th Shock and Vibration symposium) I reviewed our capabilities in simulating nuclear blast and shock environments, emphasizing large-scale field testing. In preparing today's talk, I found it interesting to reflect on progress made in nuclear weapons effects (NWE) simulation over the intervening 11 years. In many respects it is clear that we are still doing most of the same things, only better, as one would hope. Then I was fairly optimistic in anticipating improvements in HEST-like techniques and in simulations of cratering and crater-induced ground motions. Indeed, these have come about, but mostly as a consequence of massive support for superhard technology which I did not entirely forsee. The most progress, however, has been in airblast phenomenology and simulation. Eleven years ago I said

> "Airblast is the best understood of the near surface nuclear effects, both phenomenologically and in terms of an empirical data base. Still, there are thermal-related surface effects and reflection phenomena at high pressures which remain important research areas."

It may sound ok in retrospect, but in 1975 I wasn't thinking of superhard silos and hardened mobile launchers, and so I had no real idea of how important these research areas would become, or of the progress that would be made in a few short years.

As you know, the Shock & Vibration symposium is sponsored in rotation by the Air Force, Navy, Army, NASA and DNA. At the beginning of my talk I expressed the common desire that there would be a symposium next year. Let me be more optimistic and look forward to being with you then and when DNA again is the sponsor.

EFFECT OF ESM ON SIS LIMITING PERFORMANCE
750 psi CRUSH STRENGTH BACKFILL

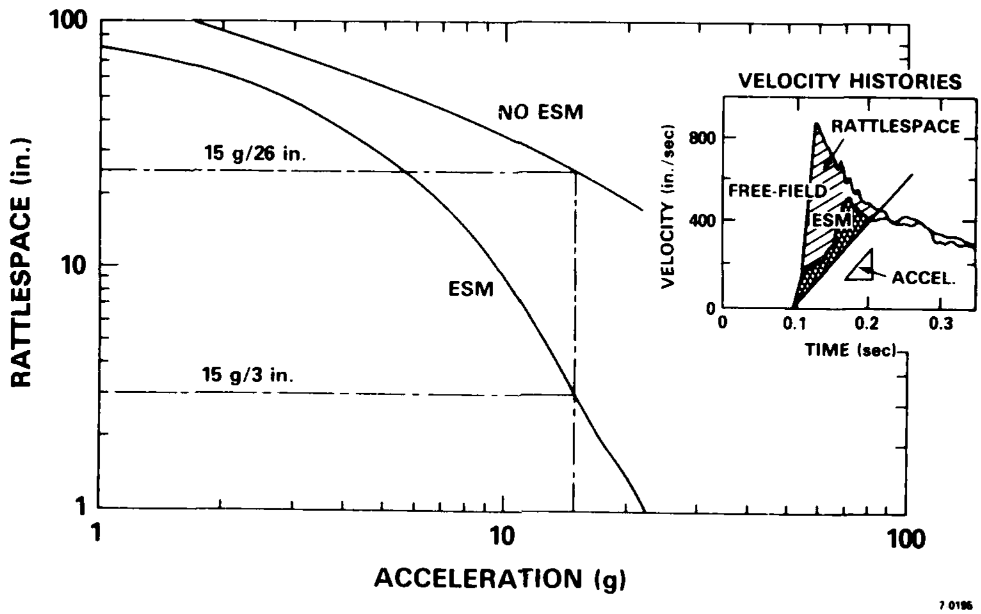


Fig. 7 — Effect of ESM on SIS limiting performance

INVITED PAPERS

RESEARCH AND DEVELOPMENT
The U.S. Army Corps of Engineers

BOB O. BENN
Assistant Director, Research and Development Directorate
(Military Programs)

The U.S. Army Corps of Engineers (CE) maintains a broad program of scientific and engineering research and development, covering virtually all the disciplines essential for support of its civil and military missions. Services are also provided to other governmental agencies on a reimbursable basis. The Corps contributes to National and Army goals in a number of ways, i.e., Support on the Battlefield, Support in Garrison, Mobilization, and Civil Works.

The Civil Works mission serves a dual purpose of developing the Nation's water resources while keeping the engineers ready to respond to national emergencies with state-of-the-art engineering. The Civil Works Research and Development Program is directed toward improving the CE capability to combine an effective, economical water resources mission and program with environmental protection and safety. Special emphasis is placed on ecology, environmental quality, and energy and water conservation.

The Military RDT&E program supports the Corps' mission as a combat arm of the U.S. Army, as a principal combat support component of the Army, and as the military construction agent for the U.S. Army and U.S. Air Force. A major component of this research is in support of the Corps' responsibility for the environmental sciences, i.e., atmospheric, terrestrial, and topographic sciences. This research is conducted at all Corps laboratories and provides the Army with tools to plan and execute the land battle. Emphasis is on space technology, topography, target acquisition, mobility, countermobility, survivability, and general engineering. Research to support CE responsibilities in base support and military construction provides new technology to reduce the costs and increase the efficiency of the military construction process, to assist facility engineers in the efficient operation and maintenance of Army installations, to improve the environmental quality at Army installations, and to reduce energy consumption and dependence on petroleum-based fuels.

The Directorate of Research and Development and its subordinate CE laboratories perform R&D to permit the CE to perform its wide-ranging mission in the most effective and efficient manner possible. The CE R&D program totaled approximately $324 million in FY86. Approximately 30 percent was directed toward Civil Works with the remaining 70 percent ($226 million) focused on the military mission. Thirty-four percent ($77 million) of the military funding was direct allotted and 66 percent ($149 million) was for reimbursable projects from DARPA, DNA, DMA, AMC, TRADOC, TACOM, AR, Navy, and other Federal agencies.

The R&D program is conducted at four CE installations. The U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, MS, is a laboratory complex containing the Structures, Hydraulic, Environmental, and Geotechnical Laboratories plus the Coastal Engineering Research Center. The other three Corps laboratories are the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH, the U.S. Army Engineering Topographic Laboratories (ETL) in Fort Belvoir, VA, and the U.S. Army Construction Engineering Research Laboratory (CERL) in Champaign, IL.

WES has a full-time permanent staff of 1,526 and is the largest research, testing, and development facility of the U.S. Army Corps of Engineers. Its mission is to conceive, plan, and execute engineering investigations and research and development studies in support of the civil and military missions of the Chief of Engineers and other Federal agencies. Work includes the broad fields of hydraulics, soil and rock mechanics, earthquake engineering, concrete, expedient construction, nuclear and conventional weapons effects, nuclear and chemical explosives excavation, vehicle mobility, environmental relationships, engineering geology, pavements, protective structures, combat engineering, camouflage, aquatic plants, water quality, and dredged material. WES has an international reputation in airfield pavements, concrete technology, soil mechanics, hydraulics, and particularly in hydraulic model investigations as related to flood control and navigation projects. WES conducts research and development to provide a better understanding of coastal processes, winds, waves, tides, water levels, currents, and materials as they apply to navigation, recreation, flood and storm protection, erosion control, and coastal and offshore structures. The effects of Corps activities on the ecology of the coastal zone are also investigated.

ETL is the largest research and development organization of its kind in the free world. Research in photo interpretation, distance measurement, coherent optics, inertial geodesy, digital data processing, environmental design criteria, remote sensing, and computer science enables ETL to address the geodetic, topographic, and geographic information needs of the Army and the Department of Defense. A significant portion of ETL's mission that addresses both military and civil users is devoted to providing scientific and technical advisory services, particularly in the areas of mapping, terrain analysis, and survey. ETL has approximately 300 full-time personnel.

CRREL has a staff of nearly 300 full-time employees. It supports civil and military construction through research investigations and engineering studies pertinent to cold environments. Its mission includes general materials research, techniques, and equipment design for cold regions and basic research in such terrestrial sciences as geoelectricity, heat flow, geochemistry, and glaciology, plus the mechanics of snow, ice, and permafrost. A major research effort at CRREL is to study the effects of winter conditions (snow, ice, fog, rain, and cold) on military operations and materiel.

CERL explores the life-cycle requirements of facilities from design through construction, operation, and maintenance to eventual replacement. This involves research and engineering studies in materials, energy, construction management, and environmental quality. Over 200 full-time employees work at CERL.

Examples of recent military research accomplishments include: (1) Life Cycle Cost in Design and Analysis System, (2) Washrack Design for Armored Vehicles, (3) Voice Activated Inspection System, (4) Plasma ARC-Spraying Technology for EMP/Tempest Protection, (5) Armored Vehicle Hardstand Designs, (6) Training Area Management Systems, (7) Training Area Noise Warning and Mitigation Systems, (8) Wheels vs Tracks Mobility Evaluations, (9) Alternate ACCESS/EGRESS Surfacing, (10) Rapid Airfield Repair Demonstrations, (11) Standoff Mine Detection Concepts and Equipment, (12) Facilities Multispectral Camouflage Techniques, (13) Sand-Grid Protective Revetments, (14) Cold Regions Impact on E/O and mm Wave System Performance, (15) Winter Bridging Criteria, (16) Combat Environment Obscuration Handbook, (17) Impact of Snow on Explosive Mine Neutralization, (18) Concepts and Technologies to Exploit the Battlefield Environment as a Combat Multiplier, (19) Quick Response Multicolor Printer (QRMP), (20) Digital Topographic Support System (DTSS), and (21) the Modular Azimuth Position System.

The CE research products, especially those coming from environmental science programs, support a wide range of Army materiel acquisition activities. A major initiative includes the CE AirLand Battlefield Environment Thrust (ALBE) that addresses environmental impacts on weapon and logistical system performance. To ensure insertion of this technology early in the development cycle, the CE participates fully in the TRADOC/AMC Mission Area Materiel Plan Process. Further, AMC and CE have developed an MOU that provides a mechanism for coordinating tech base research and emphasizes CE laboratory product handoff to AMC.

The previous discussion presented a general overview of research directed by the CE. The CE has also been involved in research of direct interest to this symposium since the early 1950's, when water shock testing was begun at WES. The first unclassified paper found referenced was presented by Messrs. R. W. Cunny and W. E. Strohm, Jr., on the response of impulsively loaded square footings on Frenchmen Flat silt. The paper was presented at the 29th Shock, Vibration and Associated Environments Symposium, which was hosted by Field Command, Defense Atomic Support Agency. Since that time, CE personnel have presented numerous papers on soil-structure interaction, in-structure shock, water shock, instrumentation and nondestructive testing techniques. The first nondestructive test of a large, full-scale structure was presented by WES personnel at the 48th Symposium. The test being reported on was the vibration test of the Perimeter Acquisition Radar (PAR) building of the Safeguard system. The PAR building is 120 by 120 feet in plan and approximately 120 feet tall. Floors were 3 feet thick and the walls were 7 feet thick at the foundation, tapering to 3 feet thick at the roof. It was quite an accomplishment to vibrate the entire structure with a single vibrator on the roof. This type of testing has become common since those early days. The CE's participation in these symposiums has increased dramatically over the years with papers being presented by both Laboratory and Division engineers. WES and DNA were co-hosts for the 52nd Symposium, as they are for the 57th Symposium. This year approximately 14 papers are being presented by CE personnel on topics ranging from the shock environment in high hardness structures being evaluated for missile silos to instrumentation and new simulation techniques.

To conclude this discussion, details of three important ongoing research programs (Protection from Terrorist Attack, Deliberate Hardened Facilities, and Army Protective Shelters) are given.

The CE has the prime responsibility for the design and construction of most U.S. military facilities throughout the world. With the ever increasing terrorist threat (Figure 1), a need exists for methods of improving the security of these installations.

WES is supporting this goal by conducting research on the response of conventional buildings (Figure 2) to a variety of terrorist threats, such as small arms, antitank rockets, mortars, and vehicle bombs. Perimeter blast walls are also being investigated as a means of reducing blast damage. Both tests (Figure 3) and analysis (Figure 4) are being used to develop guidelines for protecting our military facilities. This research is being coordinated closely with the U.S. Army Engineer District, Omaha, which has the responsibility of developing guidelines for the consideration of terrorism at all Corps facilities and construction projects. The research is also being closely coordinated with other DOD Laboratories, the Department of State, and foreign governments. Several papers on this topic will be presented at the symposium during the next three days. One problem in the area of structures hardened to conventional weapons is the shock environment created inside a structure due to the detonation of a bomb outside. Even when structural damage is light, the shock environment may be severe enough to cause damage to personnel and equipment. WES recently completed a series of tests on a 1/4-scale model (Figure 5) and a full-scale (Figure 6) hardened structure at the White Sands Missile Range (WSMR), New Mexico. Bare and cased charges were detonated at various standoffs from the structures to give structural damage ranging from slight to heavy (Figure 7). Accelerometers on the floor, roof, and walls recorded the in-structure shock environment. Typical items of equipment (Figure 8) were also included in the full-scale test. Data from these tests are currently being evaluated and will be used to develop a prediction method for in-structure shock for aboveground buildings.

In the area of combat engineering, the Corps has the responsibility for the development of hardened fighting positions and emplacements. In cooperation with the Chemical Research Development and Engineering Center (CRDEC) two buried protective shelters were selected for chemical protection upgrading. The shelters are in Army Field Manual FM 5-103, "Survivability," and Army Technical Manual 5-302, "Army Facilities Components Systems." One shelter is a 12-man concrete arch designed for a 100-psi overpressure nuclear battlefield environment (Figure 9). The second is a metal frame/fabric buried shelter for four men designed for a 30-psi survival level (Figure 10).

Tests were conducted on the two shelters by WES and CRDEC to determine size requirements for collective protection equipment and structural modifications necessary to chemically upgrade the two shelters. Both shelters were modified and evaluated at the MINOR SCALE nuclear simulation event conducted at the WSMR in June 1985. The shelters were equipped with collective protection equipment, blast valves, and blast and gas closures. Damage to the concrete arch shelter, tested at 100 psi, was minor (Figure 11); however, the chemical protection level of the fabric/frame shelter tested at 30 psi was degraded when the fabric material at the entry shaft tore and a low-level pressure (4 psi) entered the shelter compartment (Figure 12). The internal blast and shock environment was monitored inside both shelters during the test. Although the collective protection equipment survived the blast and shock environment, the life expectancy of the filters was reduced.

A series of small high-explosive (HE) tests were conducted on the concrete arch shelter after the MINOR SCALE Event. A TNT charge equivalent to a 155mm artillery shell was used for these tests. Standoff distances of the charges were reduced until severe damage to the shelter components resulted (Figure 13). Both shelters were successfully upgraded to provide protection from chemical weapon effects. An XM 20 SCPE (Simplified Collective Protection Equipment) was used with the shelters. The XM 20 is recommended to provide filtered air and positive pressure control for these and similar shelters. Production of the XM 20 system has started and wide distribution to Army units is expected to begin in 1987.

Figure 1. Damage due to terrorist car bomb.

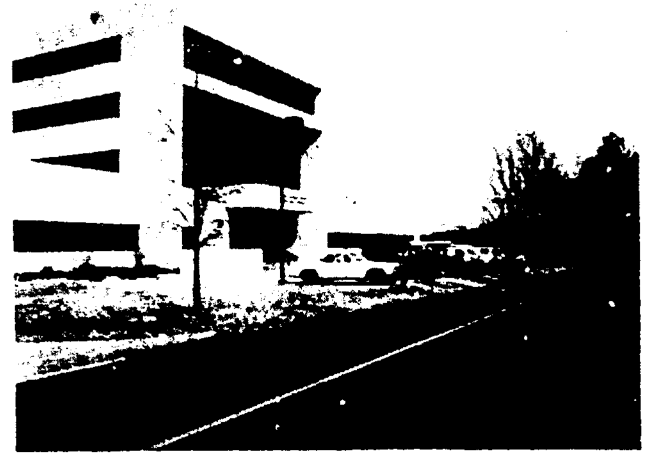


Figure 2. Typical Government building requiring protection from terrorist attack.

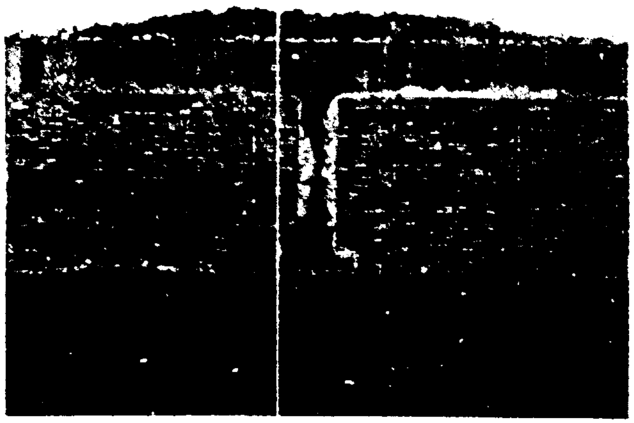


Figure 3. Blast effects on masonry walls.

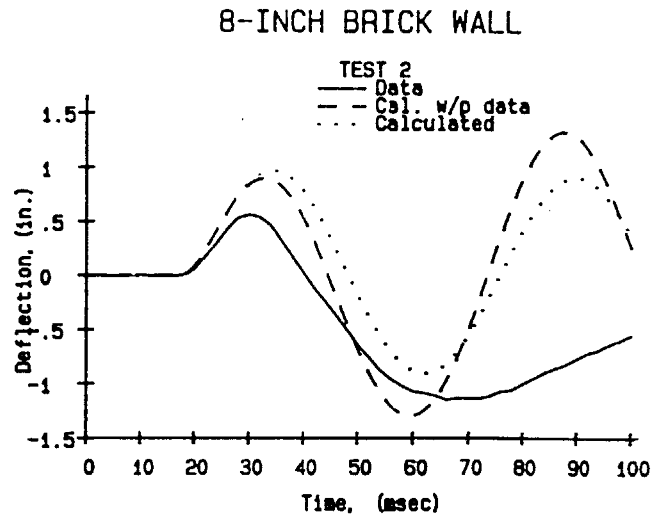


Figure 4. Comparison of calculated versus actual deflection of blast-loaded masonry walls.

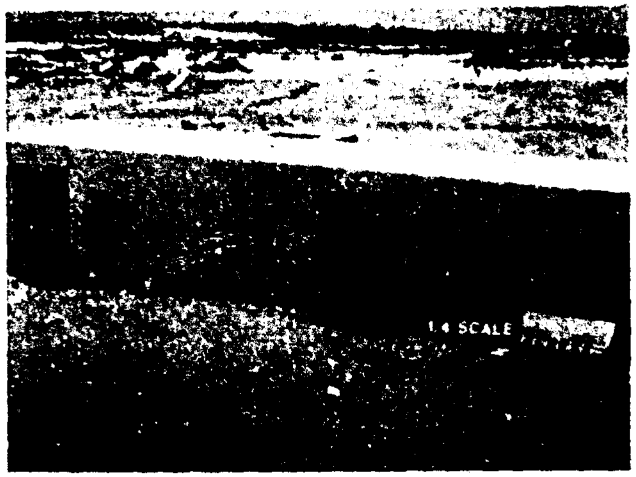


Figure 5. One-fourth-scale hardened aboveground personnel shelter.

Figure 6. Full-scale hardened aboveground personnel shelter with cased charge in place.

Figure 7. Results of cased charge test.

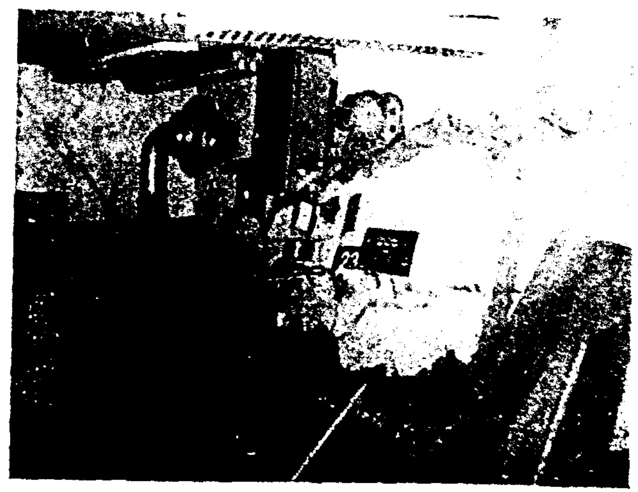


Figure 8. Posttest view of air filteration equipment inside shelter.

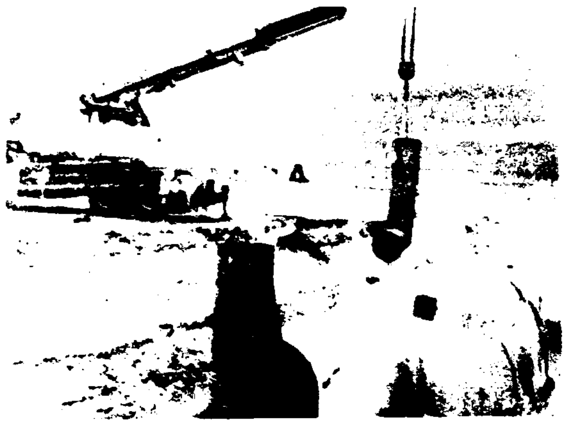


Figure 9. Construction of concrete arch personnel shelter.

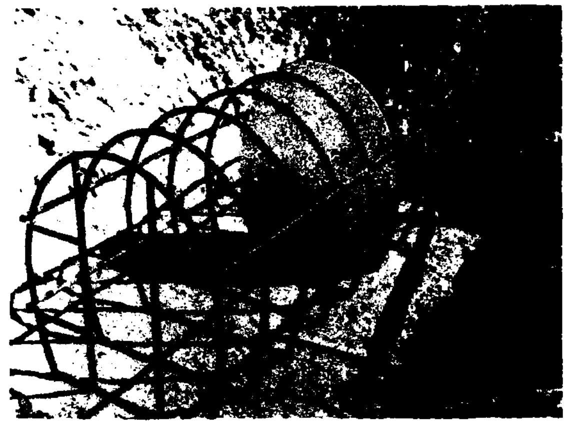


Figure 10. Construction of frame/fabric personnel shelter.

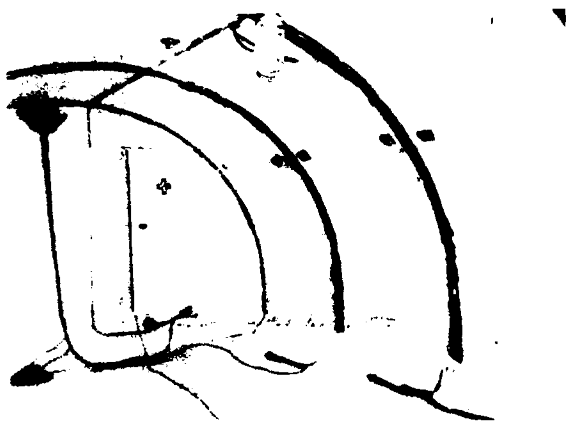


Figure 11. Posttest interior view of concrete arch shelter.

Figure 12. Posttest view of entry shaft of frame/fabric shelter.

Figure 13. Concrete arch shelter after high-explosive test.

NDI FROM A MANAGER'S POINT OF VIEW

Robert R. Lehnes
Deputy Project Manager
Mobile Subscriber Equipment
Fort Monmouth, New Jersey

Non Development Item, NDI, has become the preferred acquisition strategy in DOD. It saves R&D dollars and puts needed technology into the hands of the troops earlier than any other approach. But it is not a panacea. One particular NDI acquisition, the Mobile Subscriber Equipment (MSE) system, is discussed along with the myths of NDI and the challenges facing the NDI manager.

INTRODUCTION

NDI, Non Development Item, has become a buzz-word in DOD acquisition circles. And for good reasons. It saves precious R&D dollars and puts new technology into the hands of the troops much quicker than the traditional development process. But, is NDI a panacea? Does it solve our biggest acquisition complaint, namely that it takes too long? Well, maybe yes; but maybe no. This paper will discuss NDI as seen through the eyes and experience of a manager who has dealt with NDI for many years and is now involved in managing the largest NDI acquisition ever attempted by the Army.

To obtain a better feel for the type of acquisition we will be discussing, it is worthwhile to spend a little time with some background information. The paper is organized as follows:

- o System Description
- o Acquisition Strategy
- o NDI Myths
- o Challenges for the NDI Manager
- o Conclusions

SYSTEM DESCRIPTION

Why do we need MSE? (See Figure 1). Today's system is too expensive, it ties us to wires and cable, requires too much manpower and is immobile. That is why we're buying MSE. MSE is a cost and manpower effective communications system. All those bad things we see in Figure 1 are improved with MSE. All the "ilities:" survivability, adaptability, reliability, flexibility, etc., are enhanced with MSE.

We like to call MSE "the Bell System of the Battlefield." Because that is precisely what it is. Everything you would need in the Bell System to make a telephone call from your home or from a mobile cellular radio/telephone in your car are the things that the MSE system does for the Army on the battlefield. MSE totally integrates all of the functions of a communications system. Transmission equipment, switching equipment, COMSEC, system control, vehicles, generators, are all part of the MSE system and are being bought from a single contractor.

MSE is the first time that the Army has ever acquired a totally integrated/turn-key communications system from one contractor.

So you can better understand the MSE system, I will now describe the five functional areas of the system. The first functional area is the subscriber terminals. Subscriber terminals are the things that you would have in your hand to communicate over the MSE system; for example, telephones, facsimile machines, alphanumeric terminals for data processing/communications and mobile radio/telephones. Those items constitute user equipment. Mobile subscribers

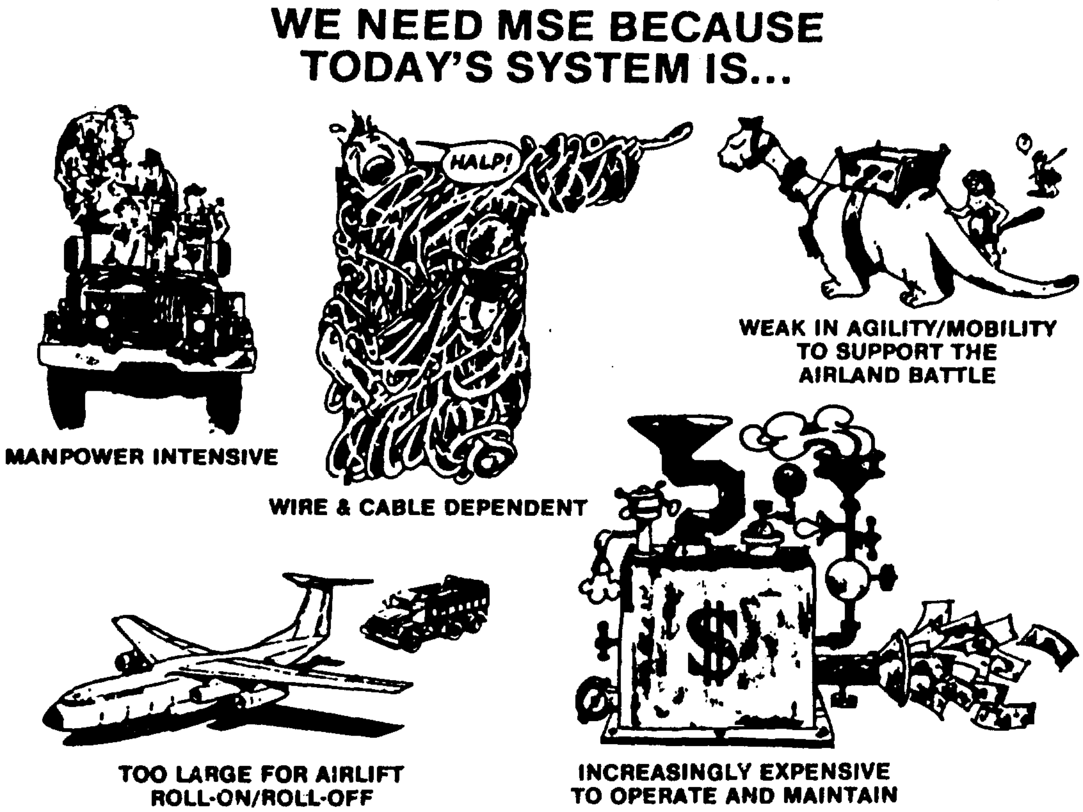


Fig. 1 - Why do we need MSE?

are provided access to the system. Whether you are in your jeep or other vehicle, or at your command post, you can have a radiotelephone and be constantly in communication with the system throughout the corps area. At command posts or large headquarters where there are high concentrations of wire subscribers using telephones, the system also provides access for those subscribers. This access to the system comprises the second and third functional areas; that is, wire subscriber access and mobile subscriber access.

The area coverage network is the fourth functional area and ties it all together via automatic circuit switches connected by Line-Of-Sight radios. And lastly, the system control functional area manages the entire network and controls the whole system for a corps and the five divisions.

Figure 2 is a very difficult chart to understand; however, if explained in terms of the five functional areas, it is really helpful in understanding the MSE system architecture. The chart shows a corps area with the squares representing a large headquarters or large command posts with the diamonds being smaller ones. The area coverage network consists of the triangles which are the node centers and the jagged lines which show that the node centers are all connected by radio to permit coverage of the whole system. The next part of the system is the extension access to the system. The large and small headquarters are served by extension switches which are connected by radio to the node central. Mobile subscribers are then connected to the node centers through the circles which are radio access units. The mobile subscribers talk through the radio access units into the system. When you put it all together you get a really complicated chart, but that's a true depiction of the architecture of the MSE system.

MSE IS THE BELL SYSTEM OF THE ARMY

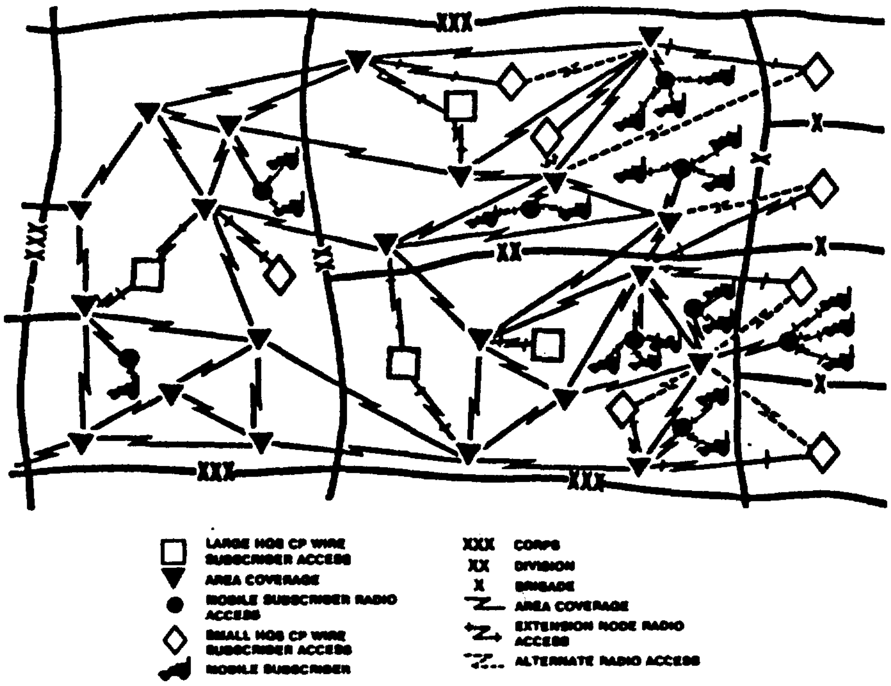


Fig. 2 - MSE System Architecture

ACQUISITION STRATEGY

I will now move on to the MSE acquisition strategy. MSE is the largest communications acquisition ever attempted by the Army. It is a 4.3 billion dollar acquisition program. We are going to buy this system and field it to the U.S. Army Active, National Guard and Reserve Forces at the same time. We have never done that before. The Reserves have always gotten the leftovers. We are going to be giving them MSE at the same time. This means that when called-up, the supporting units will be able to communicate immediately with their parent units and become instantly an integral part of the communications system.

The basis of the MSE acquisition strategy came from high levels in the Army and is very unconventional. We provided a general performance requirement to the bidders, rather than provide detailed specifications or drawings. Contractors came back and bid what their system would do. They were required to bid an existing system which, in fact, is what NDI is all about. Acquisition regulations were waived as necessary by the MSE program. Naturally, we had to comply with the statutes, conform to law, but were allowed to waive any acquisition regulation we wanted to. That's a first. We encouraged the use of commercial practices. We told bidders to come in and tell us what they have and to bid it the same way they always do it -- not to do it differently just because they are bidding it to the Army. We wanted to buy an existing system "warts and all." The system exists and that is what we're going to buy. We'll adapt the Army to use it -- not the other way around.

The Request For Proposal (RFP) contained only five required features that the system had to do. Those were the five functional areas. The contractor could bid anything as long as it did those five things. We are buying a complete system. For the first time we bought a pure turn-key system from a contractor. We are not going to Government-furnish anything to the contractor, GTE. They are to provide the trucks (the HMMWVs) which they will buy from AM General. They will provide generators, shelters, communications-electronics; everything including training, fielding, and logistics support. We didn't mandate military specifications. They told us what their system would do and we decided if that was good enough. We didn't tell them how to do it, we let them tell us.

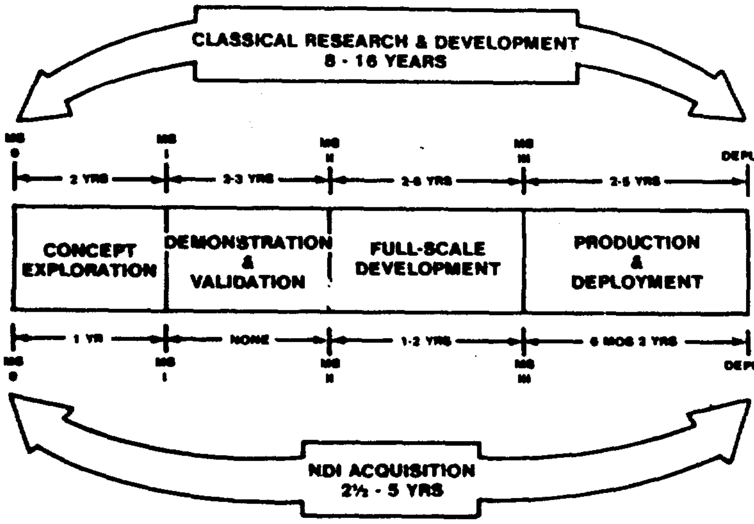


Fig. 3 - Acquisition Life-Cycle Model

The MSE Contract is a firm fixed price contract with six priced options. We have range quantity options for additional equipment. The contractor was required to bid not only basic hardware and initial spares but also spares and logistics support for fifteen years after we field the last system. Those are fixed prices adjusted only for escalation. We have fixed prices obtained in a competitive environment for the entire life cycle of this system.

Figure 3 shows the standard acquisition life cycle and how NDI differs from it. As you can see, NDI can save a considerable amount of time in the acquisition cycle of a system or equipment. Although the chart shows the entire acquisition cycle, the real difference with NDI occurs in the middle two phases. The standard life cycle has what we call a concept exploration phase, which leads into demonstration and validation followed by full scale development and then into production and deployment. The only difference in NDI is those two middle phases. Demonstration and validation and full scale development are combined into one phase in NDI. This phase has been referred to as the acquisition documentation phase. Now what do we do during that time? That's when we prepare the RFP, after we have decided to go NDI, receive proposals and evaluate them. That's the difference between the two life cycle models.

Everyone knows the three milestone decision points in the standard acquisition cycle, but how did we obtain these decisions in the NDI MSE acquisition? The Milestone I decision was basically a memo from OSD to the Undersecretary of the Army which stated that a DSARC wasn't needed and left the decision up to the Army. Later, the Undersecretary directed an NDI procurement. We moved out. In NDI you don't need a Milestone II decision because you're not going into that phase. Milestone III is your production decision and your type classification and normally you have a formal IPR or an ASARC/DSARC review council at whatever level to give you the go ahead. There are some important things needed for a Milestone III decision: a decision coordinating paper, a test and evaluation master plan, and a type classification package. Since we didn't do all those things, how would we fulfill the requirement for MSE? We did it as part of the source selection process. The type classification package was put together by the PM from the results of the source selection board which briefed up to the Senior Advisory Council and up to the Senior Selection Authority who was the Secretary of the Army in our case. The decision briefing on the source selection was the basis for a Milestone III decision to include the production contract award and type classification of the system.

NDI MYTHS

Next I want to talk a little about NDI myths. The first myth is that all NDI's are created equal. That is not true, because every NDI program is a different program. All are individual programs with unique circumstances. You can't apply blanket things to NDI. NDI can be as simple as buying a radio that the Marine Corps has developed. It can be buying a commercial system or equipment that meets the needs of a less stringent environment than we would normally specify. Or, it can be as complex as buying the Mobile Subscriber Equipment System. You can't put NDI in a standard-sized box because it doesn't fit. Each box has to accommodate a different size.

Another of the myths is "off-the-shelf." The shelf that this equipment is supposedly on, doesn't exist. I looked for that shelf. There's nothing there and we all know that. I mentioned waivers to Regulations. That's another myth. We did get a lot of waivers for acquisition regulations when we were going through the MSE acquisition but we still had to justify a lot of what we were doing. Although we got the waivers, we know that somewhere down the road someone is going to come back and say, "You didn't comply with this. You'd better do it." You have to be atuned to that and know what things you didn't do and be prepared to address them when they surface. Sometime ago I was asked by LTG Skibbie, DCG AMC, to do a review of the MSE acquisition cycle. What he asked me to do was to compare what we did on MSE with the standard model -- what things didn't we do and why. Is somebody going to come along two years from now and bite us in the tail and say, "You didn't do this. You'd better get your act together." So I did it. I took every single document, the decision point briefing papers and all the acquisition regulations and showed him either why we didn't do it, why it wasn't needed or how we got the necessary information. Everything we would have done in a normal development we had to do on MSE. We had to generate those documents. Some we didn't do when we would normally have done them but have had to do them since. For example, with the Computer Resource Management Plan (CRMP), we didn't even know what computer resources we were going to have, so we couldn't do it until after award. The type classification package, as I said before, was part of the evaluation board report. The bottom line is that we really didn't get away with much being NDI. We had to go through the same types of things that would be done on a normal development program and that's a key point. The result of the briefing, and LTG Skibbie agreed, was that we satisfied the intent of all decision milestones and documentation requirements that are in the standard life cycle management model. We satisfied every one of those, whether we actually did it or not. The point is, we satisfied the <u>intent</u> of those documents. We saved two to six years of development time and probably half of a billion dollars in R&D costs. Perhaps most important, we're going to get MSE into the hands of the troops in about five years; a substantial decrease over other methods.

Blanket relief to policy is another myth. A lot of people called our office to remark on this and said "I heard you went NDI and got relief from all kinds of things." Sure we did that, but once we awarded that contract, all of those policies started appearing on my desk. The Army secure lighting program, chemical agent resistive coating paint and tri-color camouflage are all coming across my desk now. So if you think you're getting away with something, it's not true. About the only common line I can thread through NDI, is that it doesn't spend R&D dollars. You can use R&D dollars to try to make an NDI decision by making market surveys or investigations to see what's out there. You <u>can</u> do that using R&D dollars. But once you're on contract you can't use R&D for anything relating to NDI procurement; however, you can use R&D dollars to look into potential product improvements to the program.

Another myth in my mind is, "better is better." When you're utilizing the NDI method, better is <u>not</u> necessarily better. One of the things that we have done <u>so</u> wrong for <u>so</u> long is trying to improve things that we haven't even gotten out into the field yet. Let's buy what exists today; and, if it's better than what we've got now, let's put it out in the field now. That's one of the challenges we need to put on industry: stop trying to market improvements on something when we haven't put it in the field yet. Let's concentrate on getting it out there in the hands of the troops and <u>then</u> let's talk about improving it.

Still another myth is the "cookbook" approach. You take NDI, add dollars, and you come out with a product at the other end that meets the Army's needs. There's no cookbook for NDI. There are some pamphlets and manuals that the AMC and TRADOC community have published on NDI, but these are certainly not cookbooks. They don't tell you how to do it. You have to go into each program and face each little inchstone, each major milestone, each little wicket, one at a time. There just is no easy way. We, at PM MSE, were lucky because we had very competent and very strong guidance from the highest levels of management in the Army that allowed us to do the innovative things that we did. Without that guidance we probably would still be floundering with the sixth generation of the RFP.

CHALLENGES FOR THE NDI MANAGER

Switching now to the challenges that face the NDI manager, we find that he cannot just sit back and wait for his system to be delivered. One of the biggest challenges to be faced is how do we insure that what we've selected as NDI, whether commercial off-the-shelf or otherwise, will meet the Army's needs once delivered. As an example, let's discuss how we are going to be satisfied that MSE will meet the shock and vibration environment of the field Army.

First, I'll discuss the test and evaluation philosophy we are using on MSE. MSE will be evaluated continuously throughout its acquisition cycle. This continuous evaluation program is divided into four phases. The first phase was prior to award of the contract. The bidders were required, as part of their proposal, to submit test plans, procedures, data and reports to substantiate the specified performance of their offered system. This data was evaluated as part of the source selection process. In addition, an actual demonstration of the performance of their offered system, in the field, was also required.

The second phase occurs during the production leadtime of the system. During this period several tests are conducted. Contractor development tests are run on any new or modified pieces of equipment. These tests are witnessed by the Government. As equipment builds up into the sub-system, assemblage and system level, additional tests are run such as the production reliability acceptance test and the product assurance test and evaluation. The latter test, a formal Government test, ends up at the totally integrated system level.

The third phase consists of the initial acceptance and fielding of the system. During this phase a destination (field) final acceptance test is performed followed by unit training. The unit then conducts a field training exercise which prepares them for the final "proof of the pudding," a follow-on-test and evaluation conducted by the Operational Test and Evaluation Agency. If successful, the Army will then field MSE to the entire active, reserve and national guard components. Subsequent to fielding, the last phase of the continuous evaluation program will consist of fielded system reviews and sample data collection.

Shock and vibration requirements have been considered from the start. The request for proposal asked potential bidders to submit evidence that their offered system would meet the shock and vibration environment of the field. Such evidence took the form of performance/product specifications and test plans/reports. This data was evaluated as part of the source selection process. The key here, of course, is how to insure that the product the contractor delivers withstands the environment he said it would. The first thing we did was to make the product specification submitted with his proposal part of the contract and, thereby, under government configuration control. The other thing we did was to take the shock and vibration requirements (et al.) of the specifications and make them a part of the contractor's testing program. We, therefore, have shock and vibration requirements for each piece of equipment specified in the system, government configuration control over them, and requirements for test on the first system procured and periodically during production.

Another challenge, especially for MSE, is funding stability. We cannot afford to go through budget cuts every single year. Particularly on this program, we have a five to six year program at a firm fixed price. If we are cut funds, we have to renegotiate the contract. We can't do that. One more challenge that I see, is to fight off the "weenies." The PM is probably going to spend much of his effort fighting off those little guys that have their own Army program or requirement that they have to see put on your NDI program. All of these well-meaning individuals are going to come out of the woodwork and try to force their special interests onto the NDI program. Our responsibility is to say, "No. We are not going to do that."

Another challenge to the manager is probably one of the biggest ones for the PM. It is known as "requirements creep." We must not let ourselves get into the mode of allowing additional requirements to creep into the system that didn't exist there before. There are a lot of things that would be nice to have that we might want to get out there. But we must buy what it is we signed up to buy and worry about these "nice-to-haves" later. Yet another challenge relates to industry and its role as an NDI team player. I mentioned before that marketing tries to go beyond what it is the product does now. I'm not criticizing industry for marketing, because that's their job -- to find new places for new products and new markets. That's fine; but, on certain NDI programs, we need to push what exists today and get it out there to the soldier. We can't over-market programs.

The final challenge I'd like to discuss, but certainly not the last or least one for the NDI manager, is logistic support. Most, if not all, NDI's will not come with the standard logistics support package needed by the Services. For this reason, sustainment of the NDI after fielding must be considered during the preparation of the solicitation. Such things as the use of commercial manuals, contractor testing, training and maintenance support, availability of spares and repair parts, etc. must all be considered early-on to ensure the supportability of the NDI.

CONCLUSIONS

NDI is here to stay. It will be the primary acquisition strategy of the near future. But it is not a panacea. The NDI manager must recognize that his program is unique and must tailor his strategy according to its needs. NDI doesn't get the manager "off-the-hook" for anything. You must be prepared to address all those things you would be asked to in a normal full-scale development acquisition. If these things aren't being asked of you now, cheer up, they will be eventually. Be prepared for them!

I like to consider NDI as having ended as soon as you award the production contract. NDI is just another way to get there. The contract should have adequately covered the logistics supportability of the system to include training if necessary. The contract must also specify the product you are acquiring; not just "Brand X, Model 123." Put in a product specification, even if it is only the contractor's commercial vendor sheets. Make him live up to them. That way, you won't be surprised with the Chevy that is delivered when you thought you'd ordered and paid for a Cadillac. Don't accept, "It's NDI. You take what you get."

I described the NDI acquisition of the MSE system and, as you've seen, it is unique. I hope it will shed some light on a few of those unknowns that face future NDI managers or at least prepare you for them. NDI is a new way of doing business, and all of us on the DOD/Industry acquisition team must do our part if it is to succeed.

DYNAMIC TESTING—SEVEN YEARS LATER

Allen J. Curtis
Hughes Aircraft Company
El Segundo, California

INTRODUCTION

At the 50th Shock and Vibration Symposium in October 1979, the writer had the privilege of addressing the initial Plenary Session and chose the topic—"Dynamic Testing—How Far We've Come—How Much Further To Go." For this final plenary session, it is appropriate to look back to that occasion and see what progress has been made in the seven intervening years.

In that address, three test equipment limitations and four test requirement shortcomings were highlighted as needing future development. At a rate of one per year, we would now have taken care of these problems. However, progress was not as fast as one would hope and only one test equipment limitation has been significantly eased and only two of the requirement-shortcomings can be considered to have been ameliorated. On the other hand, the intervening period has been marked by the following gains: 1) Increased versatility of digital controllers to synthesize more realistic test conditions; 2) Issuance of MIL–STD–810D in mid-1983 which "legitimized' test tailoring, 3) General acceptance of the need for broadband vibration screens and 4) Maturing of the application of TAAF and CERT testing.

EQUIPMENT LIMITATIONS

The prior paper identified three desirable developments to reduce vibration test costs. Of the three, only the development of low cost vibration systems for production vibration screens appears to have made any progress. It seems that the greatest impediment to further progress in this area is the unjustified insistence on using systems which can provide excitation controlled to tightly specified spectral characteristics. Later paragraphs will return to the subject of vibration screens. The suggested development of controllers which can be "multiplexed" to control several tests simultaneously has not occured, even though it appeared very desirable in 1979. It is likely that the reduction in cost of single controllers more than offset the cost of the added software complexity for multiplexable systems. However, the third suggestion to develop the software to perform online response control tests is still a very desirable development. Online response control becomes even more desirable with the opportunity to specify such tests more frequently as we tailor the requirements as mandated by MIL–STD–810D.

REQUIREMENTS SHORTCOMINGS

Four shortcomings within the vibration community were suggested in 1979 and, unfortunately, they seem to be with us still. Briefly, these limitations were and are:

1. Insufficient understanding of the limitations of our knowledge.
2. Use of undue conservatism and overspecification.
3. Inadequate analytical and experimental treatment of the effects of impedance match/mismatch.
4. The need to develop innovative requirements, test methods and facilities to meet the overall needs for environmental qualification, reliability development/demonstration, Mission Profile Testing and manufacturing screening.

Of the above limitations, certainly the fourth has received the most attention, particularly with the issuance of MIL–STD–810D and its mandate to tailor requirements. An excellent review of some aspects of these developments was presented by Burkhard in 1985 [1,2].

However, four inconsistencies in requirements seem to occur very frequently. First, it seems a contradiction to permit zero failures in a qualification test at extreme stress levels for an equivalent operational lifetime while permitting an "acceptable" failure rate during a reliability test conducted at relatively benign stress levels for only a fraction of a lifetime.

Second, it seems inconsistent to specify requirements for a reliability development or, more importantly, a reliability demonstration test which, from a cumulative damage viewpoint, are equivalent to several qualification tests.

Third, specification of vibration screens at the outset of a development program seems frequently to become the driving design requirement, which is certainly not the intent of vibration screens. As will be discussed later, it is more effective to merely specify that vibration screening will be employed rather than attempt to specify a screening level a priori.

Last, although not uniquely of concern with vibration screens, the specification of a certain "failure-free" period during the application of the ESS is of questionable merit. It is contradictory to the purpose of screening, which is to precipitate flaws, i.e. cause failures, and has no quantitative meaning re field reliability since it is a short time duration under an inappropriate environment.

As the recipient of requirements documents that frequently contain some or all the above inconsistencies, one has the impression that inadequate "systems engineering" is performed by the preparing activity, whether Government or contractor. Also, for whatever reason, participation by personnel with the knowledge to resolve such inconsistencies is not sought during the preparation of the documents. Let it be hoped that these problems are not an omen for the age of "tailorability".

VIBRATION SCREENING

A significant proportion of the prior paper was devoted to a discussion of the requirements that a satisfactory vibration screen must satisfy. It was postulated that the efficacy of the screen would be very tolerant of variations in the spectrum provided:

1. The spectrum is reasonably continuous, with no wide holes over a frequency range embracing a number of modes of the item being screened.
2. The overall level is appropriate.
3. The spectrum shape is essentially unspecified and uncontrolled.

Since that occasion one further vital ingredient was realized and can be summed up, somewhat rhetorically, by the statements—

RESPONSES PRECIPITATE FLAWS—
INPUTS DESCRIBE SCREENS.

In other w rds, a fourth requirement is that the screening vibration excite sufficient internal responses at the location of the flaws to precipitate them. This level has been dubbed the "Flaw Precipitation Threshhold" (FPT). If the FPT were known, then an appropriate vibration screen, defined conventionally as an input, could be developed rationally from the results of a vibration survey conducted analogously to the thermal surveys performed in connection with reliability tests. However, as yet, the FPT is unknown. A program is underway at Hughes, with Navy sponsorship, to determine the FPT from more than a hundred measurements on a variety of equipments (non-HAC) at the locations of workmenship defects uncovered during vibration screens. The results of this study will be published in early 1987 and will, hopefully, permit the rational development of appropriate vibration screening inputs.

VERSATILITY OF DIGITAL CONTROLLERS

To conclude this review of dynamic testing, perhaps the most encouraging development is the versatility inherent in digital vibration controllers which can be used to advantage now that "tailoring" has become legitimate. Three instances of this versatility will be described briefly. In 1965, the writer described an analog system to perform "Combined Broadband and Stepped Narrowband Random Vibration[3] which today is known as "random on random" [the narrow bands are swept rather than stepped]. The 1965 system handled three spikes and required tracking filters, servo amplifiers, a program tape, etc., in addition to the normal analog controllers. Today, a floppy disk with the appropriate software is all that is needed to have five spikes as mandated by –810D for tracked vehicles.

In 1970, the writer described a system for pulse testing to simulate the complex periodic vibration, i.e. line spectrum, generated by aircraft Gatling guns.[4] The test was quite complicated to set up and, in effect used the analog controller in an open loop or manual mode in conjunction with a specialized pulse generator. Today, using a digital controller, it is only necessary to synthesize a Fourier spectrum with the proper relative amplitudes. The transform of this spectrum to the time domain is then used as the required time-history and is applied repetitively to the shaker with the digital controller in a closed loop transient test mode. As described by Cies[5,6], the desired pulse rate is achieved by capturing the controller clock and changing it until the desired pulse rate is achieved. This method was extended recently to create lower frequency line spectra, such as listed in Table I. The requirement does not specify the relative phase between the lines so that the possible waveforms are infinite. One waveform which satisfies Table I is shown in Figure 1. Again, the controller clock is captured to slew the controller to the required frequency. The three hour duration for the test was accomplished as 54,000 transients performed nose-to-tail! The most difficult part of the test is to document that the test was run at the proper frequency, since the entire digital processing, including the post-test documentation, is slaved to the same clock and is unaware of the slewing of the controller. It should be evident that a digital controller can be used to create any waveform whose Fourier spectrum can be synthesized in computer normal time and, by time compression, or expansion, adjusted to any desired frequency.

TABLE I. LINE SPECTRUM AMPLITUDES

Frequency (Hz)	Amplitude (g)
11.25	1.4
16.875	1.4
22.50	1.4
33.75	1.4
56.25	1.2
67.5	1.2

The above capability, which has been known for some time, then leads to the following application for transient testing. It was desired to perform a transient test so that the peak acceleration of masses M1 and M2 in Figure 2 reached prescribed values, with the acceleration of M2 roughly double that of M1. Further, the natural frequency of M2 on M1 was approximately 17 Hz. It was determined that a single wavelet of acceleration with a wavelet frequency at about 12 Hz would provide the desired amplification of the M2 response.

A wavelet can be readily synthesized on the digital controller. A Fourier spectrum with a single-frequency component can be transformed to a sinewave. Applying a Hanning window to the sinewave forms the wavelet. The waveform shown in Figure 3 is a 10 Hz wavelet with a time duration of 200 msec, while Figure 4 shows a 20 Hz wavelet with the same duration. The shock spectrum of this latter waveform is shown in Figure 5. It is noted that for a Q of 10, the maximum response is approximately four times the input, i.e., this is the maximum amplification that can be achieved with this wavelet. A wavelet with more oscillations will, of course, achieve greater amplification. For the particular controller, *transient control requires a 200 msec time duration.*

The 200 msec duration corresponds to a 5 Hz resolution in the frequency domain. Therefore, the most straight forward approach to create a 12 Hz wavelet would be to synthesize a 10 Hz wavelet and speed up the clock. Since the 10 Hz wavelet occupies the second spectral line of the controller input spectrum, the controller was unable to satisfactorily equalize to the desired waveform. Figure 6 shows the waveform at normal clock speed. Therefore, a 20 Hz wavelet, i.e., the fourth line of the spectrum, was tried. The improvement in the achieved waveform shown is evident in Figures 7 and 8 which are for normal clock speed and slewed to approximately 8 Hz, respectively. Figures 6, 7 and 8 were measured on a bare table. Figure 9 shows the waveform achieved at 12.5 Hz with the table loaded by the test item.

The technique for frequency slewing of a transient is different from that for vibration testing in that it is necessary to equalize at low level as the clock frequency is slewed in relatively small increments from the nominal to the desired frequency. Thus for the test described above, it was necessary to shock at low level in the vicinity of the 17 Hz resonance as the clock was slewed from 20 Hz to 12.5 Hz. Excessive response was avoided during the slewing process by performing the slewing 15 db below the desired test level and by "jumping across" the resonant peak.

It is evident that it is possible to conduct transient tests employing any waveform that can be synthesized in the Fourier processor and then slewed to the desired duration. The only limitation is the inherent displacement limitation of the shaker. Use of oscillatory waveforms such as a wavelet minimizes the velocity change associated with the pulse and, therefore, the maximum displacement.

SUMMARY

The preceding sections of this paper have attempted to briefly review developments in dynamic testing since a prior review in 1979. Not surprisingly, the paper has dealt with those areas with which the writer is most familiar, i.e., those in which he has been working. The corollary to this is that developments is other areas, such as the use of multiple random excitation in modal testing, have not been addressed. The writer apologizes for these unavoidable omissions.

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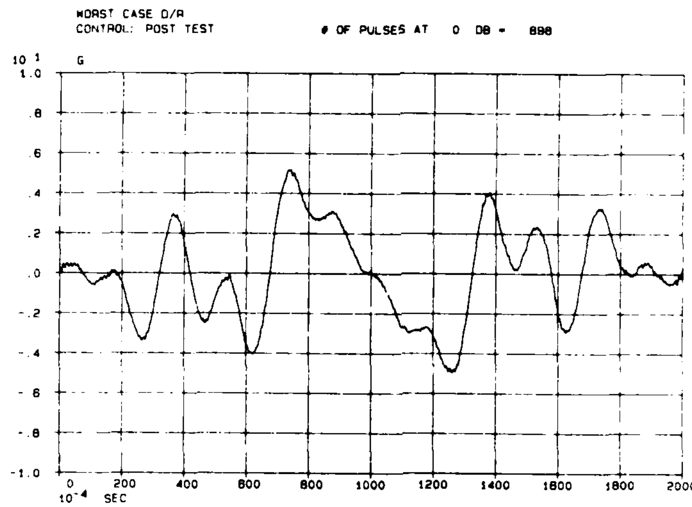


Figure 1. Time-history for line spectrum of Table I.

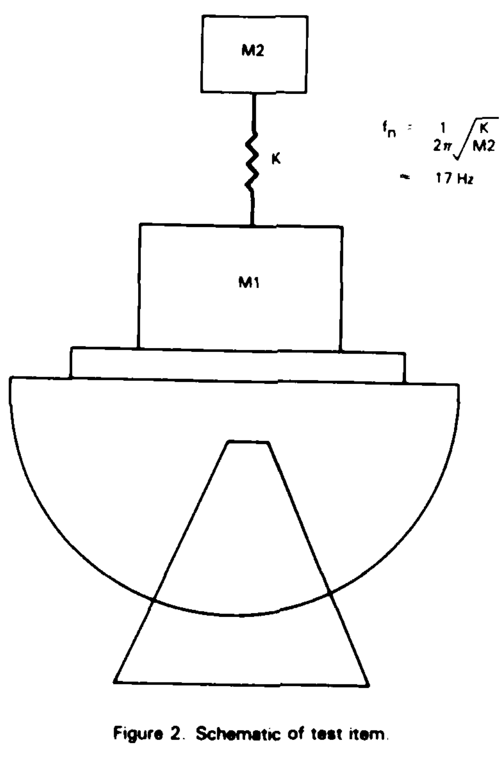


Figure 2. Schematic of test item.

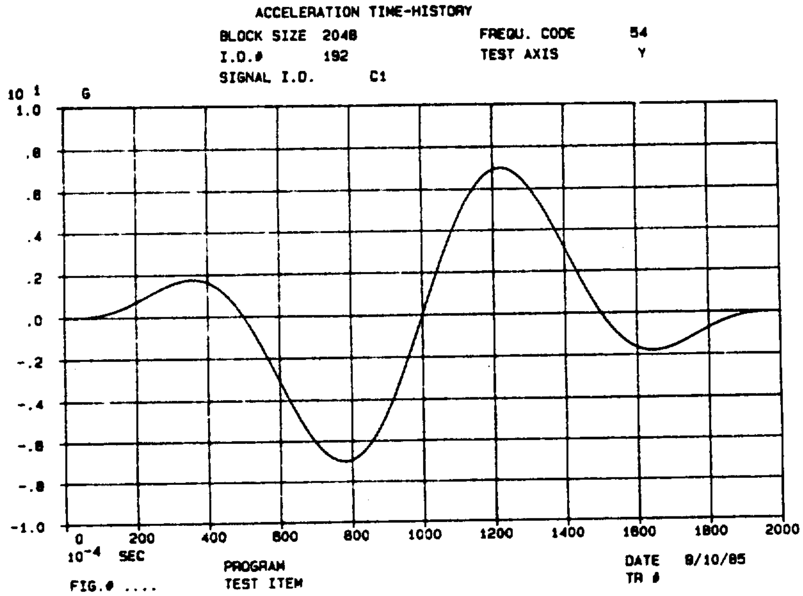


Figure 3. 7g—10 Hz—200 msec wavelet—nominal.

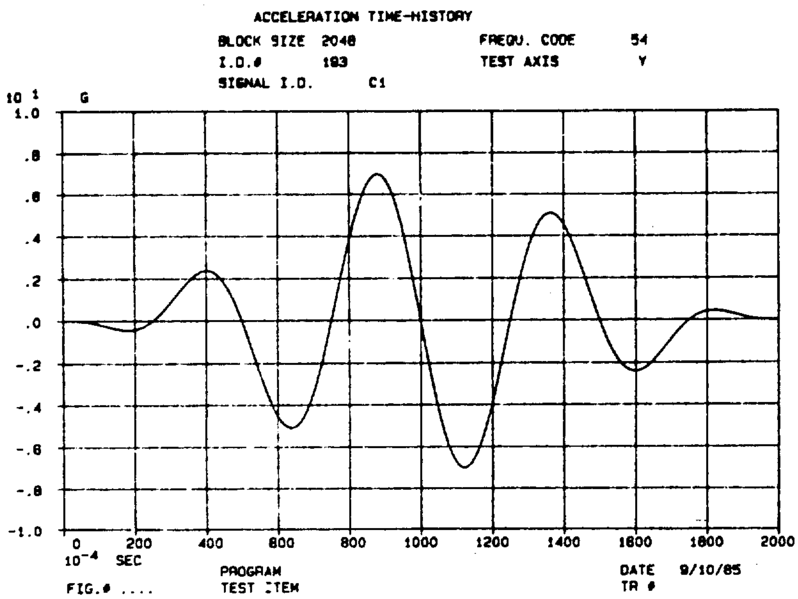


Figure 4. 7g—20 Hz—200 msec wavelet—nominal.

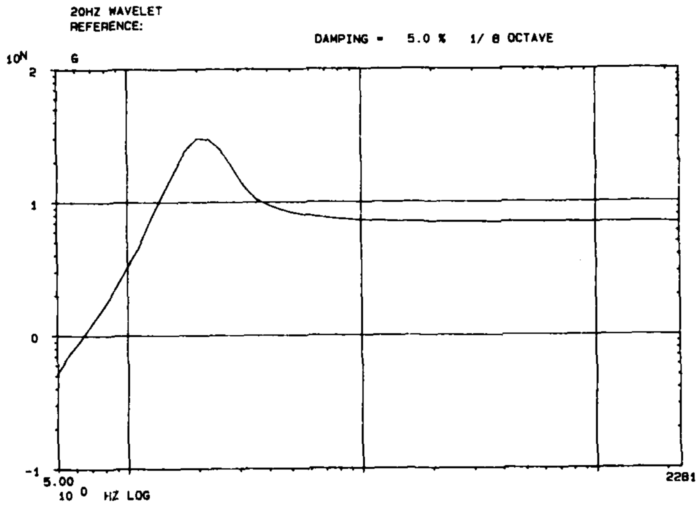


Figure 5. Shock response spectrum of Figure 4.

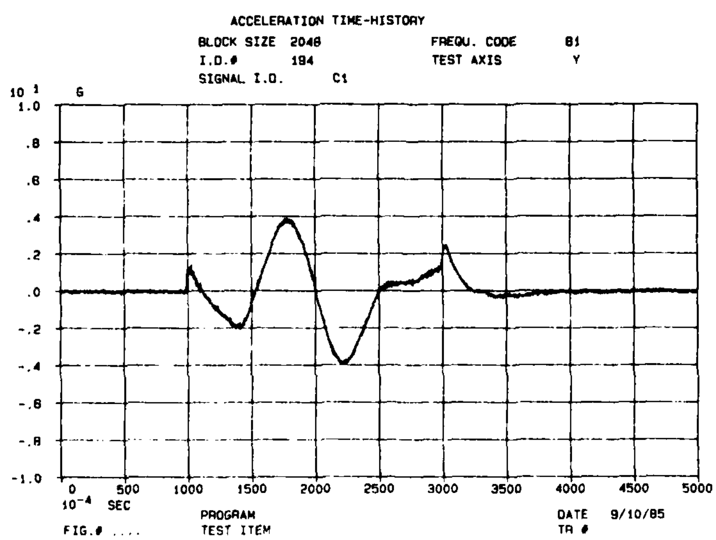


Figure 6. 4g—10 Hz—200 msec wavelet—control accelerometer—bare table.

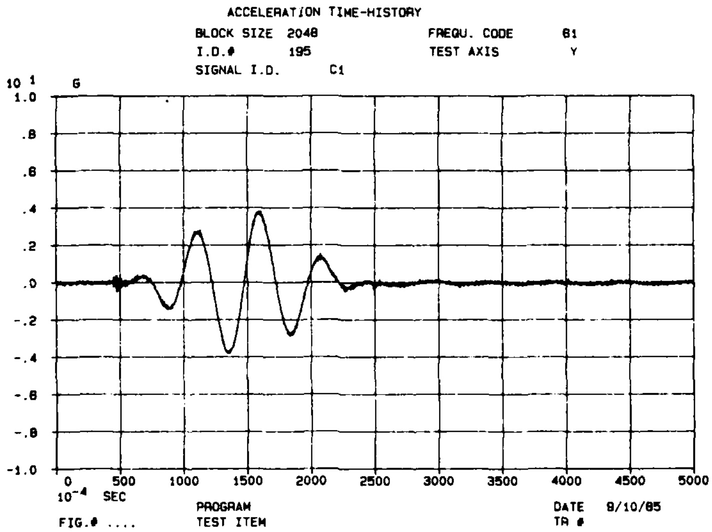


Figure 7. 4g—20 Hz—200 msec wavelet—control accelerometer—bare table.

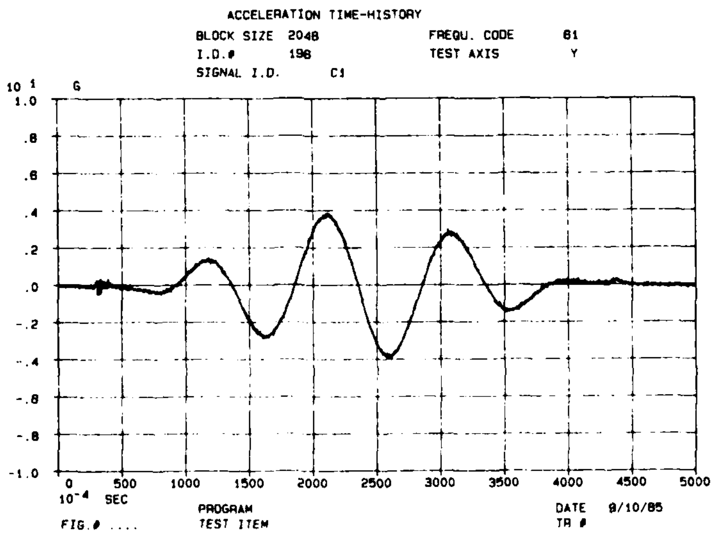


Figure 8. 4g—20 Hz—200 msec wavelet slewed to 8 Hz—control accelerometer—bare table.

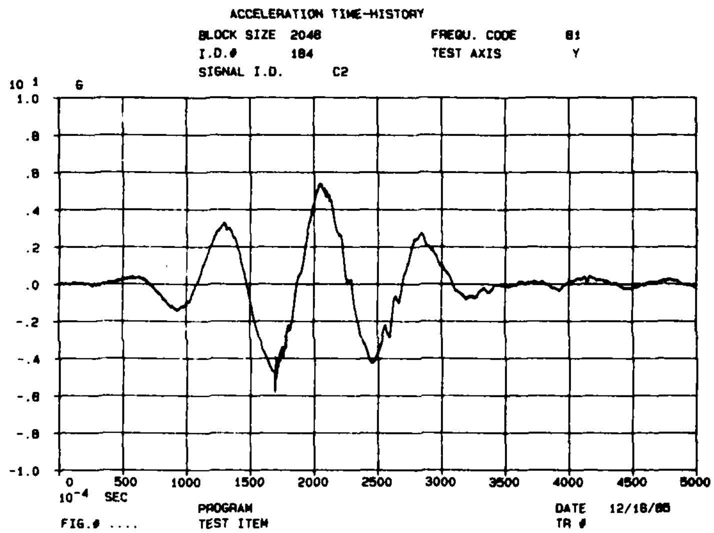


Figure 9. 5g—20 Hz—200 msec wavelet slewed to 12.5 Hz—320 msec—control accelerometer—loaded table.

GUIDELINES FOR QUALIFYING NON-DEVELOPMENT EQUIPMENT TO SHOCK AND VIBRATION

Clark J. Beck, Jr.
Boeing Aerospace Company
Seattle, Washington

The equipment costs for new vehicles can be substantially reduced if available equipment is used, thereby saving development costs. Further cost reductions can be realized if shock and vibration qualification testing can be eliminated. This paper presents guidelines for determining if a non-development equipment item is suitable for use on a new vehicle without additional vibration and shock testing. These guidelines have been successfully implemented on several programs. Using these guidelines, it was possible to reduce the number of tests on one program by 92%.

INTRODUCTION

The development and qualification costs associated with aircraft and space vehicle equipment is a significant portion of the total vehicle development costs. One way to minimize these costs is to use available equipment on new vehicles thereby eliminating equipment development costs. The equipment costs can be reduced even more if qualification tests can be eliminated or minimized. This paper presents guidelines for determining if a non-development equipment item is suitable for use on a new vehicle without additional vibration and shock qualification testing. These guidelines have been developed over the last 15 years and have been successfully implemented on several Boeing programs.

ENVIRONMENT QUALIFICATION PROCESS

Flow Chart

The shock and vibration environment qualification process for non-development equipment (NDE) is illustrated in figure 1. The details of each step in the flow chart are discussed in the following paragraphs.

Define New Environment

The new vehicle environment must be defined to provide design requirements for the NDE. The requirements should be defined in terms of maximum expected environment and qualification test requirements. Acoustic noise and steady state acceleration as well as shock and vibration should be included in the definition . The number of occurrences and the duration of the maximum levels for each environment should be noted . Since environments are generally expressed as envelopes, a document should be prepared explaining how the envelopes were derived and identifying any factors applied to the levels or durations.

Determine NDE Environment

The vibration, shock, acoustic noise and steady state acceleration design and test information must be obtained for the NDE. The basic types of information needed are design requirements, test requirements and test results. The information provided by sales brochures is not what is needed. What is needed are engineering and test laboratory documents which define design and test

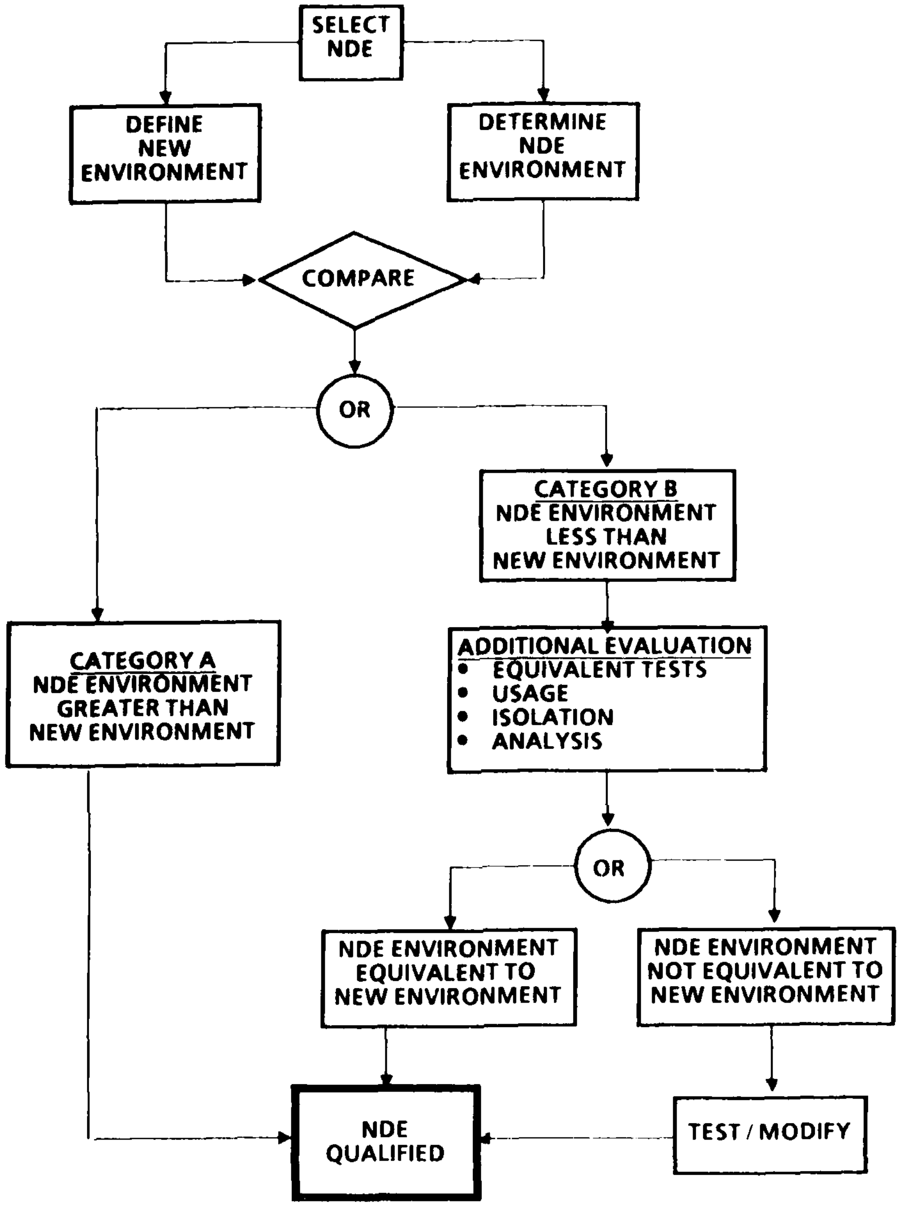


Fig. 1 - NDE Environment Qualification Process

requirements and demonstrate how the requirements were met.

Compare New and NDE Environments

The environments for the new vehicle are then compared with the environments for the NDE to determine if the equipment is compatible with the new environments. The comparisons should consider each environment individually. The results of the comparisons should be documented. These environment comparisons will place the NDE in one of two categories. For discussion purposes the categories will be referred to as A and B.

Category A refers to NDE designed and tested to environments which meet or exceed the environment design and test requirements for the new vehicle. Category A equipment can be used on the new vehicle without further analysis or testing. Category B equipment refers to NDE which has not been designed or tested to one or more of the new vehicle environments. When NDE is placed in Category B this does not necessarily exclude the use of the NDE on the new vehicle. There are evaluation techniques other than strict level and time comparisons that can be used to demonstrate environment compatibility. The evaluation techniques we have found most useful are discussed in the following paragraphs.

Additional Evaluation Techniques

Previous Equivalent Tests. NDE can sometimes be qualified on the basis of a previous equivalent test. Earlier in this paper under the discussion of environment definition, acoustic noise and steady state acceleration were included along with vibration and shock. These environments were included because they produce dynamic responses and loads similar to vibration and shock. When these four environments and their relationships are evaluated it is sometimes possible to show an item qualified for the new environment on the basis of a previous equivalent test. Some examples of equivalent tests follow.

1. The equivalence between sine vibration and random vibration is one of the most common types of equivalence encountered. There is considerable technical literature on this equivalence. It is not unusual to find that a new vehicle vibration environment is defined as random vibration while the NDE has been qualified by a previous sine vibration test. The random environment can be converted to an equivalent sine to determine if the sine vibration test qualified the NDE for use in the new random vibration environment.

2. Acoustic noise tests are often required for NDE. Experience has shown that if NDE has been qualified to random vibration then in most cases it is qualified for use in an acoustic environment. Therefore, it may be possible to satisfy an acoustic test requirement on the basis of a previous equipment random vibration test. MIL-STD-810 discusses the relationship between noise and vibration testing.

3. The lower frequency of random vibration environments are commonly defined at 10 Hz or 20 Hz. The lack of vibration definition below 10 or 20 Hz raises a question relative to the ability of the equipment to withstand vibration below these frequencies. A previous steady state acceleration test along with an analysis that shows no equipment resonances at the low frequencies can be used to demonstrate qualification for the low frequency environment. Conversely, vibration and shock tests can produce loads which are greater than the steady state acceleration requirement. Therefore, previous equipment qualification for vibration and shock can often be used to satisfy the steady state acceleration design and test requirement.

Previous Usage. By definition NDE has been developed for and used in other vehicles. Therefore, it is worthwhile to contact the NDE manufacturer and determine if the equipment has been used on vehicles similar to the new vehicle. If the applications appear to be similar, then further information should be gathered to verify environmental similarity between the vehicles and to verify that the equipment is performing satisfactorily in service. When environment similarity and satisfactory service history are established, then the NDE can be qualified by previous usage.

Isolation. Shock and vibration isolators can be used to lower the levels transmitted to an equipment item. This technique can be used when the new vehicle environment is higher than the NDE environment. The isolator transfer function is applied to the new environment and the resulting environment is compared with the NDE capability. If the NDE environment on isolators is less than the NDE capability, then the NDE is qualified for the new environment. This technique appears to be an ideal solution for adapting NDE to a new environment. A word of caution is in order. An isolator will always result in magnification of the applied environment at some part of the frequency range. The new vehicle environment and the NDE capability must be considered in the isolator design to insure that the new environment is not magnified by the isolation system to a level which exceeds the NDE capability.

Analysis. Analysis can be used to show that the NDE is compatible with the new vehicle environment. For example, a new environment for NDE used in an aircraft might be crash load accelerations. A stress analysis of the NDE is a practical technique for demonstrating that the equipment can withstand the loads thereby satisfying the design and test requirements.

Combination. A combination of the above techniques is often used to demonstrate that the NDE is qualified for the new vehicle environment.

Test / Modify

Although additional evaluation may show that the NDE is compatible with the new vehicle environment, the additional evaluation may indicate that testing and/or modification is required to demonstrate NDE compatibility with the new vehicle.

APPLICATION

These guidelines were applied to a program where 65 items of NDE were to be installed in a new vehicle. The design requirements specified vibration, shock, acoustic noise and acceleration environments. The requirements presented the possibility of 260 environmental tests, Table 2(a). Table 2 (b) shows the number of potential tests which were eliminated by previous test, equivalent test, etc. Note that only 20 tests were required out of a potential 260 tests. Table 2(c) indicates the percentage of tests eliminated with respect to the various environments. For example, 49% of the potential vibration tests were eliminated based on previous NDE usage.

CONCLUSIONS / COMMENTS

It is possible to qualify non-development equipment (NDE) for use on new vehicles without additional vibration and shock testing. This paper has presented guidelines for accomplishing qualification without additional testing. These guide-lines have been developed over the last 15 years and have been successfully used for qualifying both air and space vehicle equipment.

For a recent program 65 equipment items were required to operate in 4 dynamic environments. This requirement established a potential for 260 tests. Using the techniques discussed in this paper we were able to reduce the number of tests from 260 to 20 or a reduction of 92%.

It is not always possible to use NDE on a new vehicle without additional testing, but testing can be minimized.

These guidelines have been applied to other environments such as temperature-altitude and explosive atmosphere. The guidelines can also be used for NDE intended for vehicles other than aircraft and space vehicles.

These guidelines are not unique or complex, but their successful application requires extensive data gathering, careful data evaluation, excellent documentation and extensive coordination with the customer.

TABLE 2
Guideline Application Results

(a) GIVEN
65 Equipment Items
4 Environments Vibration Shock Acoustic Noise Acceleration
260 Potential Tests

(b) RESULTS BY CATEGORY		
Category A		
Qualified by previous test	80/260	31 %
Category B		
Qualified by equivalent test	35/260	13 %
Qualified by usage	70/260	27 %
Qualified by analysis	55/260	21 %
Additional tests required	20/260	8 %

(c) RESULTS BY ENVIRONMENT

	CATEGORY A	CATEGORY B			
		EQUIV.	USAGE	ANAL.	TEST
Vibration	18%	8%	49%	8%	17%
Shock	75%	0%	5%	11%	9%
Noise	9%	9%	54%	25%	3%
Acceleration	20%	36%	0%	42%	2%

MAJOR ACCOMPLISHMENTS OF THE AIR FORCE WEAPONS LABORATORY'S SURVIVABLE UTILITIES PROGRAM

1st Lt L.T. Nicholas and Capt G.C. Laventure, Jr
Air Force Weapons Laboratory
Kirtland AFB, New Mexico

The Air Force Weapons Laboratory (AFWL) began the Survivable Utilities (SU) Program to address the response of utility systems in conventional and nuclear weapon environments. Under this program, AFWL has field tested personnel shelter equipment, emergency power units, and power and communication cables to conventional weapon effects. Objectives, articles, instrumentation, results, conclusions, and recommendations from these tests are described.

INTRODUCTION

Under the SU Program, AFWL has field tested various utility equipment to conventional weapon environments. This paper will discuss the history of the SU Program, AFWL's experience in qualifying equipment to conventional weapon effects, three field test case histories, and a summary.

Background information, objectives, test articles, instrumentation, results, conclusions, and recommendations of each test program will be discussed. Because this paper is approved for public release, discussion of these test programs is strictly qualitative. Specific details on the type of weapon or specific environments are omitted.

A BRIEF HISTORY OF AFWL's SURVIVABLE UTILITIES PROGRAM

In January, 1983, the Civil Engineering Research Division of AFWL (AFWL/NTE) began the Survivable Power (SP) Program in response to the growing concern over the vulnerability of Air Force electric power systems to various weapon effects. Traditionally, AFWL/NTE had been concerned mainly with the structural response of a protective system to a given weapons environment. Under the SP Program, AFWL began to address the response of power equipment (generators, circuit breakers, cables) to various weapon environments.

The first field testing performed under the SP Program involved the MUST Series (June 1983-April 1984). In the MUST Series, AFWL tested both the structure and internal operating equipment of two personnel shelters to conventional weapon effects.

Initially, funding for the SP Program was small (less than $100K per year), and field testing was limited to add-on experiments on other AFWL tests.

In May 1984, the Air Base Survivability System Management Office (AD/YQ), located at Eglin AFB, Florida, requested AFWL's support in performing a bomb damage analysis for the upcoming SALTY DEMO Air Base Survivability (ABS) capability demonstration to be held the following year at Spangdahlem Air Base (AB), Federal Republic of Germany.

AD/YQ provided AFWL computer-generated bomb plots of Spangdahlem AB to be used as the threat scenario for the 5-day demonstration. From these bomb plots, AFWL assessed the bomb damage to facilities and utilities (electric power, water, communications, petroleum, oil, and lubricants (POL) and heating, ventilation, and air conditioning (HVAC)) on Spangdahlem AB.

In performing this bomb damage analysis, AFWL reviewed literature from the US strategic bombing survey from WW II as well as literature from previous testing of facilities/utilities to conventional weapon effects (CWEs). Most of the CWE's data on utilities had limited applicability to SALTY DEMO. Realizing from our work in support of SALTY DEMO that air bases rely heavily on all utilities, AFWL expanded the SP Program into the SU Program in October 1984.

AFWL, having completed the USAF's first ever on site analysis of an entire air base in September 1984, was asked by AD/YQ to help simulate the bomb damage during the SALTY DEMO demonstration in May 1985. AFWL organized and led a 35-person team of Air Force Civil Engineering personnel in disrupting and restablishing utility service (electric, water, POL) on Spangdahlem in coordination with simulated enemy air/ground attacks and base recovery actions.

SALTY DEMO made AD/YQ and the USAF fully realize the importance of utilities to ABS, and as a result AD/YQ began funding AFWL's SU Program in December 1985.

AFWL's FY 86 SU Program has grown to $600,000 and consists of two main projects, the Overhead and Underground (OHUG) Cable Survivability Program and the Air Base Utility System Survivability Assessment Model (AUSSAM) Program.

The AUSSAM Program is developing a computer model to assess bomb damage to air base utility systems from a given conventional air attack. AUSSAM will provide utility damage input to the TSARINA/TSAR code, an existing ABS code. TSARINA/TSAR will then determine the impact of utility damage to air base sortie generation.

AUSSAM will rely on existing survivability data on utility systems to predict bomb damage to these systems. OHUG and future testing programs will provide AUSSAM with updated and more accurate survivability data on utility systems.

Both the OHUG and AUSSAM efforts are receiving continued AD/YQ funding in FY 87. AD/YQ is also funding AFWL in FY 87 to begin testing POL piping systems.

Quantifying the response of various air base utility systems and their components to CWEs will require several years of research due to limited resources; AFWL will test only one or two components of utility systems per year. Eventually, AFWL wants to test suggested methods of improving utility survivability. The end product of AFWL's SU Program will be to significantly improve the Air Force's combat readiness by quantifying the conventional weapon environments, by showing the resulting effects on air base utility systems and mission, and by developing improvements to existing and future systems.

AFWL's EXPERIENCE IN QUALIFYING EQUIPMENT TO WEAPON EFFECTS

Until the SP and SU Programs, AFWL had limited experience in qualifying equipment to weapon effects. To properly qualify equipment, AFWL reviewed existing military/industrial standards and qualification programs (Seismic Safety Margins Research Program and SAFEGUARD) for qualification procedures (Ref. [1] and [2]).

Conclusions of this search were

a. No existing military standards specifically address procedures for weapon effects qualification of ground-based equipment.

b. MIL-STD-810D, the primary military standard for shock testing, is concerned almost exclusively with transport, handling, and storage environments.

c. MIL-STD-901C, a Navy standard, gives a number of procedures for qualification of shipboard equipment to weapon-induced shock environments. However, a shipboard environment is different from a ground-based equipment environment.

d. No standards exist to address qualification of equipment to blast, fragments, and debris.

Because of the lack of procedures for qualifying ground equipment to weapon effects, AFWL has used its engineering judgment in developing test procedures.

CASE HISTORIES

Under the SU Program, AFWL has field tested various utility equipment to conventional weapon environments. The following three projects are discussed: (1) the Multiunit Structure Test (MUST) Series, (2) the Generator Shelter Tests, and (3) the Overhead and Underground (OHUG) Power and Communication Cable Survivability tests.

The MUST Series tested two Chemical, Biological, Radiological (CBR) personnel shelters--the French AMF-80 and the American Design-to-Cost (DTC) shelter--to conventional weapon effects. AFWL tested both shelters with their internal equipment (generator, ventilation and air conditioning and lighting) operating.

The generator shelter test series tested expedient shelters for protecting mobile power equipment (30-kW diesel-engine generator) to conventional weapon effects.

The OHUG cable survivability tests were designed to quantify the survivability of overhead and underground power and communication cables to conventional weapon effects. The program involves field testing and development of an analytical model for predicting cable system response to conventional weapon environments.

(1) MUST TEST SERIES BACKGROUND

In 1982, the Aeronautical Systems Division (ASD) tasked AFWL to test two chemical, biological, radiological (CBR) personnel shelters--the French AMF-80 cylindrical shelter (Fig. 1) and the American Design-to-Cost (DTC) rectangular shelter (Fig. 2). Further details on the testing of these shelters can be found in Ref. [3] and [4]. ASD later changed the names of the AMF-80 and DTC to Survivable Collective Protective System-1 (SCPS-1) and SCPS-2, respectively. AFWL named the program the Multi-Unit Structure Test (MUST) Series.

All testing involved conventional weapons only. For additional protection, AFWL half-buried and bermed both shelters. During each test event, all internal equipment was operating.

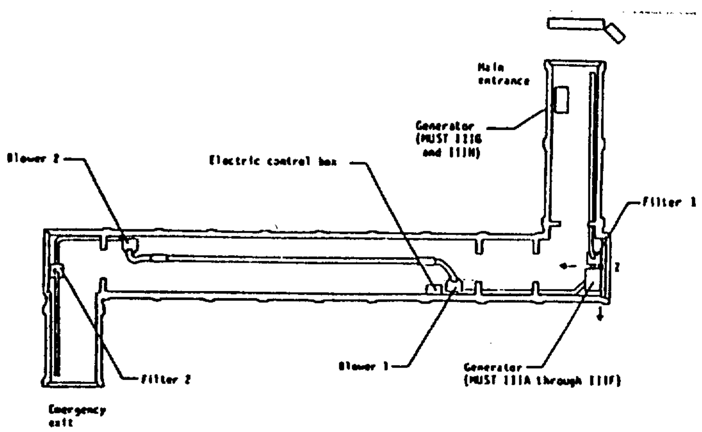


Fig. 1 - AMF-80 Shelter

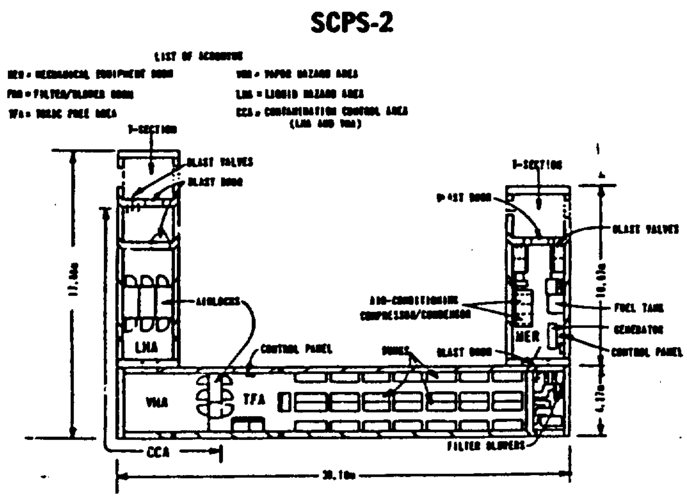


Fig. 2 - American Design-to-Cost (DTC) Shelter

The location, type of burst (buried or surface), and yield of the conventional weapon varied in each test event. AFWL performed preliminary tests on an empty cylindrical concrete structure (MUST-I) and an empty rectangular concrete structure (MUST-II) to better predict the shock environments for the AMF-80 (MUST-III or SCPS-1) and the DTC (MUST-IV or SCPS-2) test events. The SCPS-1 Series consisted of eight test events, and the SCPS-2 consisted of six test events.

From the test results, AFWL concluded both shelters are approximately equal in survivability. ASD selected the SCPS-2 shelter due to spacing considerations. The SCPS-2 is a larger shelter and its rectangular shape allows for more effective use of limited shelter spacing.

MUST POWER SYSTEM TEST OBJECTIVES

Specific objectives of the power portion of the MUST Series were:

a. Determine the survivability of the SCPS-1 and SCPS-2 electrical and mechanical systems to the imposed weapon environments.

b. Measure the electrical and mechanical response of SCPS-1 and SCPS-2 internal equipment.

c. Identify sources of electrical transients and assess their impact on equipment.

MUST TEST ARTICLES

The SCPS-1 is a cylindrical reinforced concrete structure capable of sheltering approximately 30 people.

Internal equipment consisted of a Homelite 7.4 kw, 208-V, three-phase diesel engine-generator set, two motor blowers, two air filter units, electric lighting, and one electric control box.

All equipment was hard-mounted except for the Homelite generator which had some rubber padding. The padding was for vibration isolation of the operating generator from the structure and not for shock isolation.

The SCPS-2 is a rectangular reinforced concrete structure capable of sheltering approximately 72 people.

The SCPS-2 consisted of a larger array of equipment. The power source was a 37-kW, 208/120-V, three-phase diesel engine-generator set. Shock isolation consisted of Aeroflex shock isolators designed to keep equipment accelerations to 5 g's or less. As a safety precaution, a chain and strap were fastened around the generator and its frame to prevent the generator from flying loose of its frame.

Fuel for the Kohler generator during the test was stored in a 5-gallon tank suspended from the ceiling. The normal fuel tank of 300 gallons was bolted to the floor. For safety reasons, the main fuel tank was filled with water during the tests.

HVAC equipment in the SCPS-2 included three shock-mounted motor blowers, two air compressor/condenser units (TRANE RAVE-406 Series 700), two TRANE air handler units, one electric heater, and flexible ducting. The air handlers were heat exchangers which cooled interior air by passing it over chilled water. The air handler units, motor blowers, and compressor/condenser units were shock mounted in a manner similiar to the generator.

An equipment control panel, in the Toxic Free Area (TFA) of the SCPS-2, could control all the equipment except for the generator. An electrical panel containing circuit breakers was located behind the generator in the Mechanical Equipment Room (MER). Both of these panels were hard-mounted.

The equipment, tested in these shelters, is not necessarily the same equipment that the Air Force will use in the actual deployed shelters because the USAF is sometimes required to buy support equipment, such as generators, from local vendors. The ASD selected equipment used in the test would be representative of generic families of equipment.

MUST INSTRUMENTATION

Acceleration data were of primary interest. Triaxial accelerations were recorded on equipment and on the structure. Voltage and current were recorded on electrical equipment. Incident overpressures were recorded in the air ducts and intake and exhaust manifolds of the generator.

MUST RESULTS/CONCLUSIONS/RECOMMENDATIONS

The SCPS-1 equipment survived the shock environments in each of the tests. However, in one test event, the circuit breaker for the main shelter lighting system tripped due to shock. The circuit breaker was easily reset. In the last test event, ASD asked AFWL to place the generator in the main shelter entrance behind a blast wall. ASD was concerned that the generator produced too much noise in the shelter for the inhabitants. The bomb was located a short distance in front of the blast wall. The air blast caused no damage to the generator. However, concrete spall from the blast wall hit the generator casing and pushed it into the alternator drive belt. Although the generator continued operating, the drive belt would have eventually severed if it continued rubbing against the casing.

AFWL concluded that the SCPS-1 internal equipment would continue to operate with minor damage in the selected threat environment. The generator can operate in the entrance way of the shelter. However, spall is a potential problem.

AFWL recommended that a T-shaped concrete pipe be connected to the entrance to prevent concrete spall from hitting the generator.

The SCPS-2 electrical equipment survived the imposed ground shock environments. However, structural displacement of modules caused a kink in the insulation of one of the power lines. The exposed conductor shorted to the metal conduit blowing the main fuse in the main control panel. When the main fuse blew, the entire power system went down. the electrical data showed that several of the circuit breakers tripped as a result of the short.

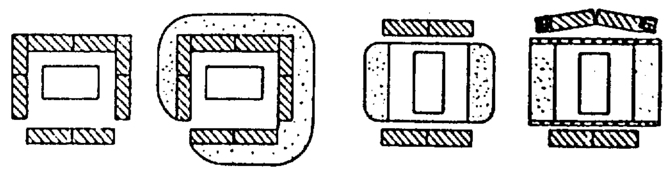
AFWL concluded that the present wiring design was inadequate for an explosive environment, and recommended replacing the toggle switches in the existing remote control panel with fusible switches. This design change would eliminate the possibility of blowing the main fuse if a short occurred in any of the lines running between the remote control panel and the circuit breaker panel.

(2) GENERATOR SHELTER TESTS BACKGROUND

The generator shelter tests initially began with the testing of Bitburg revetments as a means of protecting external equipment and buildings. Bitburg revetments are portable reinforced concrete protective barriers. The United States Air Forces in Europe (USAFE) requested AFWL test these revetments to near misses from conventional weapons. To determine the protective effectiveness of the revetments, AFWL placed an operating diesel engine-generator behind the revetments.

After the Bitburg revetment tests, AFWL designed an improved generator shelter consisting of Bitburg revetments and a bermed steel culvert. The culvert provided additional air blast protection.

Testing of the culvert-revetment showed that fragments ricocheting off the revetments into the culvert were a potential damage mechanism. To reduce this problem, AFWL augmented the revetments with sandbags. Fig. 3 shows the four shelters used to protect the generator. Further information on these tests can be found in Ref. [5].



(a) Bitburg revetments (b) Bermed Bitburg revetments (c) Bermed culvert with Bitburg revetments (d) Bermed culvert with Bitburg revetments and sandbags

Fig. 3 - MB-18 (30 kW) Generator Shelter Tests

GENERATOR SHELTER TEST OBJECTIVES

a. Determine the ability of each type of shelter to withstand fragmentation and air blast effects from a conventional weapon.

b. Determine the level of protection provided by each shelter to equipment from fragmentation and air blast.

GENERATOR SHELTER TEST ARTICLES

Test articles consisted of Bitburg revetments, diesel engine-generator set, and a steel culvert.

Bitburg revetments come in varying shapes and sizes. The type used to protect the generator is shown in Fig. 4. These revetments were unbermed and bermed as shown in Fig. 3.

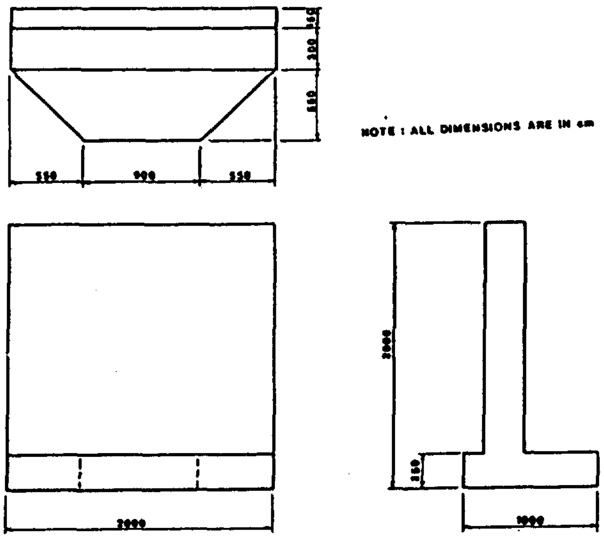


Fig. 4 - Bitburg Revetment

The test generator was an MB-18 diesel engine generator set manufactured by Fremont Corp. The specifications of the MB-18 are 30-kW, 60 Hz, three-phase power, 208/120V, and a power factor of 0.8. Dimensions of the MB-18 are 30 in. wide, 84 in. long, and 46 in. high. The MB-18 was skid-mounted with no shock isolation. During the test events, the MB-18 supplied 21 kW power to a load bank.

The steel culvert was a semicircular structure (12 ft. I.D.) which was 10 ft. long and 1/8 in. thick. The culvert was bermed with soil. The culvert shelter was first tested with the bomb radial perpendicular to the longitudinal axis of the culvert. In the second test, the culvert shelter's longitudinal axis coincided with the bomb radial. In the third culvert test, AFWL added sandbags to the revetments and culvert and tested with the bomb radial perpendicular to the culvert's longitudinal axis.

GENERATOR SHELTER TEST INSTRUMENTATION

Since all weapons were surface burst, the attenuation of the air blast in the shelters was of primary interest. Incident overpressure was recorded inside and outside of all shelters. Measurements on the generator included triaxial accelerations, voltage, and current.

GENERATOR SHELTER TEST RESULTS/CONCLUSIONS/ RECOMMENDATIONS

Both the unbermed and bermed revetments prevented fragments from reaching the generator. The earth berms extend the usable life of revetments during a period of multiple attacks.

The revetments significantly reduced the air blast. However, the air blast did cosmetic damage by bending the metal casing of the generator. In the second revetment test, the deformation of the casing severed a battery cable resulting in a shutdown of the generator. After the test, the cable was repaired and the generator resumed normal operation.

The revetment-culvert shelter was effective against air blast. However, in the first culvert test, a fragment ricocheted off the backside of a revetment into the generator's radiator, causing a leak.

To prevent ricocheting fragments from entering the culvert, the revetments were augmented with walls of sandbags. The sandbags would prevent any fragments from having a direct line of sight with the backside of the revetments.

The sandbag walls offered effective protection from fragment ricochet. However, sandbags suffer severe fragment damage and are, therefore, a one time good deal. AFWL recommends replacing the sandbags with two more Bitburg revetments.

(3) OHUG TEST BACKGROUND

As part of the SALTY DEMO ABS bomb damage analysis, AFWL developed approximate bomb damage radii for power and communication cables based on limited conventional weapons testing and a comprehensive literature search.

After SALTY DEMO, AD/YQ funded AFWL to test overhead and underground (OHUG) power and communication cables to conventional weapon effects. The OHUG Program is a continuing FY 86, FY 87, and FY 88 effort that should better define bomb damage radii and expected failure mechanisms for overhead and underground cable systems. Only the overhead cable test is discussed in this report.

OHUG TEST OBJECTIVES

a. Determine the major damage mechanisms and quantify the expected damage radii for power and communication cable systems when subjected to conventional weapon effects.

b. Develop methods for predicting damage to power and communication cable systems in a conventional weapon environment.

OHUG TEST ARTICLES

The overhead cable test, held on 12 Jun 86, consisted of two wooden pole power and communication cable systems at different ranges from GZ, as shown in Fig. 5. All cables were unenergized.

Crossarms consisted of two types--wooden and fiber glass. Oil-filled transformers with cutouts were single-mounted on three poles and cluster-mounted (three transformers in a cluster) on another pole.

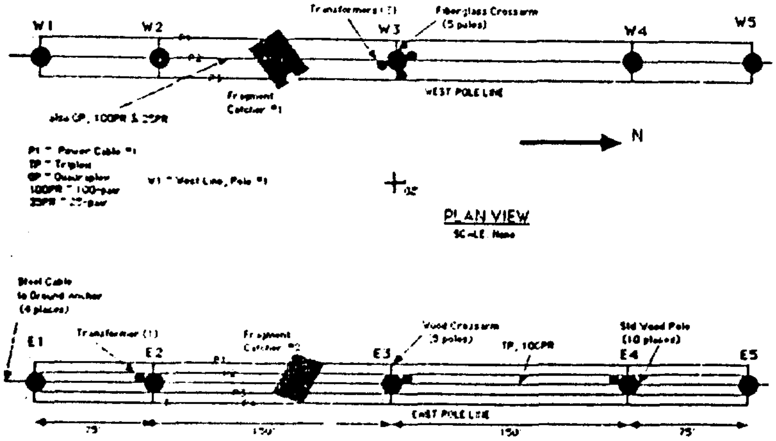


Fig. 5 - Overhead Cable Test Layout

OHUG INSTRUMENTATION

Instrumentation consisted of fragment bins, air blast gages, accelerometers, and strain gages on the poles.

One of the test objectives was to determine the size hole a given size fragment would create. Short wooden poles were placed in front of fragment bins which would capture any fragments penetrating the short poles.

Dynamic air blast pressure was another potential damage mechanism. AFWL used an indirect method for measuring dynamic pressure. Pairs of blast gages were placed at three different heights on several different poles. The first gage of each pair of gages was placed on the front of the pole to measure total (stagnation) pressure. The second gage of each pair of gages was placed on the side of the pole to measure static pressure (incident overpressure). Dynamic pressure can be calculated knowing the total and static pressures and the Mach number of the air blast shock wave.

OHUG TEST RESULTS/CONCLUSIONS/RECOMMENDATIONS

Fragments were the major cause of damage. Air blast, which travels behind the fragments at the ranges tested, failed the closer of the two center poles (W3) in shear. However, the fragments contributed significantly to this failure by weakening the pole through numerous perforations near the pole's base. All cables suffered at least one or more fragment hits, resulting in partial or complete severing of the cables.

The major conclusion was that overhead cables are extremely vulnerable to fragments. Air blast which was thought to be a significant cause of failure prior to testing was insignificant due to its short time duration on wood poles not severely weakened from fragmentation.

Since AFWL has not tested underground cables at this time, AFWL has no final recommendations on making cables more survivable.

SUMMARY

The AFWL's survivable utilities program is still in its infancy. However, systems which the SU program was involved in testing, such as SCPS-2 and Bitburg revetments, are already being deployed.

With major funding beginning in FY 86, AFWL will continue to test existing and future air base utility systems, such as power and communication cable networks. Eventually, AFWL plans to test hardening techniques for utilities.

In addition to field testing, AFWL has placed an equal emphasis in FY 86 on modeling utility equipment response in a conventional weapons environment. AFWL has developed methods for predicting cable damage and is continuing work on the AUSSAM model.

In FY 87, AFWL plans to continue analytical modeling work and begin laboratory testing of POL pipeline and power/communication cable system components. Some additional field testing of cable systems may also occur in FY 87.

Although AFWL's experience in qualification testing of equipment to weapon environments is limited compared to other major programs, its Survivable Utilities Program is beginning to answer major questions concerning the vulnerability/survivability of air base utility systems. In the future, the USAF and other DOD agencies need to consider designing utility systems not only with peacetime reliability and maintainability, but also wartime survivability.

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A CASE HISTORY OF THE QUALIFICATION PROGRAM CONDUCTED BY THE U.S. ARMY OF THE GERMAN 120MM TANK MAIN ARMAMENT SYSTEM FOR THE M1A1 ABRAMS TANK

Howard L. Bernstein
Office of the Project Manager, Tank Main Armament Systems
Dover, New Jersey

This case history presents a brief description of the testing and qualification program in the area of Shock and Vibration done on the 120mm German Tank Main Armament System in adapting it to the United States Abrams Tank.

This case history presents the program that the United States has successfully conducted to qualify the German 120mm Tank Main Armament System for the adoption to the United States M1A1 Abrams Tank. The specific area of concentration will be in the area of Shock and Vibration testing and some unique problems and solutions that developed due to the design of the ammunition and the fact that the system was not developed by the United States.

The program to qualify the German 120mm System for the M1A1 Abrams tank is managed by the Office of Project Manager, Tank Main Armament Systems (OPM, TMAS). This office was established in 1979 after the decision to adapt the German 120mm system to the Abrams Tank. It was decided by the Army that a dedicated Project Manager was required to manage the program in order to assure the successful transfer of the 120mm system.

The Office of Project Manager, TMAS, was located in Dover, NJ at the site of Picatinny Arsenal in that it could draw on technical support from the U.S. Army Ammunition Research, Development and Engineering Center. In order to ensure successful tank system integration, OPM, TMAS reported to the Program Manager for Tanks located at the U.S Army Tank Automotive Command (TACOM), Detroit, Michigan.

The program consisted of a License Agreement between the Government of the United States and the German company of Rheinmetall for manufacturing and data rights for the four rounds of 120mm ammunition and the 120mm cannon. The U.S. Government also purchased a know-how package from Rheinmetall. This package contained important process and manufacturing information. In addition, a Memo of Understanding was signed between the U.S. and German Government.

This was a very important document as it gave the U.S. a direct link to obtain additional information or request help if problems developed with the information received under the License Agreement.

The figure below lists the cannon and rounds covered under the License Agreement. Both the U.S. and German nomenclature is shown. In addition, the U.S developed its own modern technology Kinetic Energy (KE) round, a U.S. fuze to meet U.S. unique safety requirements, a one step metal can for shipping and ammunition storage, and selected minor components. Two significant aspects of the 120mm system is the use of a two part combustable cartridge case which is bonded together and a smooth bore chrome plated tube.

FIGURE 1

CANNON	M256/RH120
KINETIC ENERGY	XM827/DM13
KINETIC ENERGY TRAINING	M865/DM38
HEAT MULTI-PURPOSE	M830/DM12A1
HEAT TRAINING	M831/DM18

The history of the 120mm program goes back to the Tri-Lateral Tests conducted between the United States, Germany, and England during the period 1976 to 1977. As a result of these tests a Memorandum of Understanding was negotiated between the United States and Germany and signed in July 1976. Based on the Tri-Lateral tests, the Secretary of the Army chose the German 120mm Tank Main Armament System in January 1978.

The next year the United States negotiated a license with the Rheinmetall company for use of the 120mm system on the Abrams Tank. In August 1979 the U.S. Army signed a contract with Honeywell, Inc, Defense Systems Division, to perform a Technology Transfer, Fabrication and Test (TTF&T) of 120mm ammunition. The 120mm Cannon TTF&T was done at the U.S. Army, Watervliet Arsenal and Benet Weapons Laboratory in Albany, New York. The United States and Germany issued a design freeze in June 1980 in order to baseline the system. After four years of testing and building hardware the four rounds of ammunition were Type Classified in 1984 and 1985 and Material Releases obtained in July and August 1986. Over this time period, more than 20,000 rounds were built and tested.

An overall program philosophy was adopted early in the program and used throughout the TTF&T program. The six rules were as follows:

1. Interoperable system (cannon and ammunition).

2. Field Maintenance Interchangeability.

3. International Configuration Management/Interface Control.

4. Make it as the Germans do.

5. Change only when driven.

6. Field the System - then consider Product Improvements/Value Engineering proposals.

The most important rules were number 3 and 4. Develop an international configuration management system and to make it as the Germans do, which meant you had to resist making U.S. changes until the system was type classified and into production.

The three key documents used to control the international configuration management of the 120mm system was the basic Configuration Management Agreement, a set of International Interface Control Documentation and a Joint Technical Plan. These key documents controlled the configuration of the items and established a bilateral system of requesting changes and keeping each nation informed of changes and progress on the program. Periodic meetings were held of the Joint Configuration Management Board to resolve any problems and handle new situations as they developed.

Upon signing the License Agreement, initial visits were made to Germany and initial data retrieved. This initial data consisted of drawings, specifications, and test reports. The drawings were in the metric system, third angle projection.

A decision was made early in the program to keep the U.S technical package in the same system. A review of the specifications received showed that unlike U.S. specifications for similar items only a minimum amount of inspections were required and that Germany relied more on performance parameter than the United States, although even these were minimal. The methodology used was to rely on the contractor performance and Quality Procedures to control the items being built. In the area of test reports it was determined that although substantial tests had been conducted, reports were not written and where reports were written test procedures were not described in detail. The Germans in many cases had adopted standard U.S. procedures and tests to qualify their equipment. However, changes may have been made due to a unique requirement such as a vibration level or time duration. These specific areas could only be defined after detailed discussions with the actual people that conducted the tests.

Due to shock and vibration considerations during initial German testing certain changes were made in the design of the ammunition and a unique ammunition storage rack was designed. During initial vibration testing of the KE round, movement of the upper part of the combustable case caused ignition to the case. In order to strengthen the upper part of the case the material was changed to an inert composition.

The German philosophy in designing the storage rack for the tank was different than would be used in the United States. Germany selected the vibration level that the ammunition must survive. This level was based on a combination of levels used in the standard U.S. safety tests and a review of the Leo 2 tank vibration. Once these levels were selected, the ammunition was tested to ensure it would pass. Then the tank storage rack developer was instructed to design a rack and mounting that would input no more stress on the ammunition than was originally seen in the Safety Qualification tests. This required the racks to support the ammunition only in certain areas and to shock mount the entire rack assembly. In addition, a decelerator was designed at the end of the rack to slow the round down as it is stored into the rack to prevent breakage.

The initial philosophy in developing the U.S storage rack was to use the same rack that was being used for the standard 105mm system and just increase the size to 120mm. However shock and vibration tests quickly determined that the storage rack must consider the combustable case and be designed to protect the ammunition. Before a rack could be developed in the U.S. certain key ammunition development data was required.

Also a need existed to determine the various loads the ammunition would experience in loading and unloading from the racks and various vibration levels that would occur on the M1A1 Abrams tank. In addition, a method was needed to mount the racks in the tank to minimize shock and vibration loading. Based on analysis of German vibrations from the Leo II tank and test data, it was concluded that the U.S. could not just upgrade its 105mm rack but must design a new rack specifically for the 120mm ammunition. Ammunition tests were conducted to determine the chambering rate of the ammunition and the maximum pull strength that it could withstand. One hundred inches/second was the maximum chambering rate used in designing the 120mm racks. After a number of Government tests and competitive evaluations, the German company of Wegmann won a contract to design and build the 120mm storage racks for the M1A1 tank. This was the same company that designed the 120mm racks for the German Leo II tank. The following additional features were requested to be incorporated into the design; a shock absorber type latch, a nylon lip guard to protect the combustable case, a rubber "bumper" in the forward area of the rack to stop the round after it is stored, and shock mounting the racks in the tank to minimize vibration loads.

The final design of the M1A1 ammunition storage racks resulted with a design to store forty rounds of ammunition in the tank. Thirty-four in the turret bustle and six in the hull.

The Safety tests of the 120mm ammunition was conducted in accordance with the International Test Operation procedures (ITOP 4-2-504(2), 21 June 1985) developed by the U.S. Army Test Command (TECOM). Figure 2 presents a summary of the major tests of the ITOP and the ones that are pertinent to shock and vibration.

SAFETY TESTING FOR TANK AMMUNITION
(ITOP 4-2-504(2), 21 JUNE 1985)

	SHOCK	VIBRATION
1. 12M DROP (40FT)	X	
2. 3M DROP (10FT)	X	
3. PROPELLANT CHECK		
4. STRENGTH OF DESIGN		
5. ROUGH HANDLING	X	X
6. VIBRATION		X
7. STORAGE (HOT/COLD)		
8. HIGH HUMIDITY/TEMP		
9. SUPPLEMENTAL TESTS		

Each of the tests contained in Figure 2 that deal with shock and vibration will be discussed briefly. The Twelve Meter Drop test consists of an unguided twelve meter drop in the ammunition package. This test simulates an accidental drop during ship loading or unloading. The ammunition must be safe to dispose of after this test.

The Three Meter Drop test consists of an unguided three meter drop unpackaged. This test simulates an accidental drop during vehicle loading or unloading. The ammunition must be safe to dispose of after this test.

The Sequencial Rough-Handling test consists of two 2.1 meter drops packaged, a loose cargo bounce test in the package, and two drops unpackaged from 1.5 meters. All tests of this sequence is devided into two groups and half are conducted at 63 degrees C and half at -46 degrees C. This test simulates severe shocks, bumps, and drops an item may see in its use in the field. The ammunition must be safe to fire if there is no visual damage or be safe to dispose of if damaged. The Loose Cargo test conducted in this sequence is specified in ITOP 4-2-602. The test consists of packaged ammunition tested on a 1.8 meter by 2.4 meter platform. This platform is driven by a variable-speed motor that impacts a 2.5 cm circular double amplitude. Maximum output is 1.5 G at approximately 5.5 Hertz. This test is equivalent to 250 km of loose cargo transported over Belgian block. Due to the fact that the ammunition has a combustible cartridge case the 1.5 meter bare drop test was modified in order that additional ammunition would be available to fire. Experimental tests were conducted to determine the height the ammunition would survive. This height was determined to be .5 meters.

Two Vibration tests were conducted; the first, a Secured-Cargo Vibration test which simulates, the vibration ammunition would see in its standard shipping container. The second vibration test was a Rack Vibration test with the ammunition in the tank rack to simulate, the vibration the ammunition would see when transported in the tank. Both these tests are conducted with half the sample at 63 degrees C and half at -46 degrees C and then fired from the 120mm cannon. In order to develop the 120mm rack vibration test schedule a M1A1 tank with special modified racks was built and instrumented at Aberdeen Proving Ground to monitor input and output accelerations. The tank was then driven over different road covers at different speeds. Based on these data measurements and analysis the APG Environmental Test Section developed the M1A1 rack vibration schedule.

Tables were developed containing accelermeter location, axis orientation, speed and frequency range. The average RMS values were used instead of maximum values in order to lessen the possibility of overtesting. An exaggeration factor was developed to account for the reduction of real-time to laboratory test time. This factor was based on using a laboratory test time of 15 minutes for each 1609 km (1,000 miles) of operation. Total test time is based on a distance of 8047 km (5,000 miles). The curves developed are contained in ITOP 1-2-601 dated 11 March 1985.

As a result of U.S. testing and qualification, some additional changes were made. The primer metal case design was changed to prevent breakage of the primer case, and in addition, the explosive of the M830 was changed to a more producible less sensitive U.S. explosive.

All rounds have successfully passed qualification tests including design and operational tank system testing and have been typed classified for production. Material Release was completed in August 1986 and all rounds are currently in production. The M1A1 Abrams tank is scheduled to be fielded in Europe in January 1987 with the 120mm Tank Main Armament System.

Throughout the six years of the 120mm Technology, Transfer, Fabrication, and Test programs problems were encountered but these were solved through the dedicated effort of Contractor and Government personnel. In addition, when additional help was required the German Government and German Contractors actively participated, if requested. Through this team effort the qualification of the 120mm System was accomplished. Of the many Lessons Learned the most pertinent ones are summarized below:

1. MAINTAIN CONFIGURATION ON NON-DEVELOPED ITEM.

2. OBTAIN MAXIMUM DATA AND KNOW-HOW BY PERSONAL VISITS INCLUDING TEST FACILITIES AND AGENCIES RESPONSIBLE FOR CERTIFICATIONS.

3. MAINTAIN COMMUNICATION WITH DEVELOPER OF ITEM.

4. DON'T RE-INVENT THE WHEEL FOR EXTERNAL ASSOCIATED EQUIPMENT. USE EXISTING DESIGNS. ONLY MODIFY FOR U.S. UNIQUE REQUIREMENTS.

5. ADOPT AS MANY REQUIREMENTS THAT ORIGINAL ITEM WAS DEVELOPED TOO, AS POSSIBLE.

6. BE PERSISTENT.

In conclusion, the adoption of 120mm Tank Main Armament System to the Abrams M1A1 Tank has been one of the most successful Army transfers of a non-development system. The 120mm armament system gives the U.S. Army a system to meet and defeat the current threats and a significant growth potential for the future.

DERIVATION OF EQUIPMENT VIBRATION REQUIREMENTS FOR AV-8B

Dr. Theodor H. Beier
McDonnell Douglas Corporation
St. Louis, Missouri

The method used to derive vibration test requirements for AV-8B equipment procurement is discussed. The reasons why a vectored-thrust, V/STOL aircraft requires unique considerations not covered in MIL-STD-810C or British Standard 3G.100 are indicated. An approach is offered for specification of vibration requirements which incorporates these V/STOL considerations, and which accommodates the test types of either standard to the extent possible.

INTRODUCTION

The AV-8B is a subsonic, attack aircraft developed by McDonnell Aircraft and British Aerospace for the United States Marine Corps. (Figure 1) It is an extensive modification of the Hawker Siddeley (British Aerospace) Harrier which has been flown by the RAF and USMC for several years. Prior to AV-8B full scale development, an AV-8A airframe was modified incorporating the major AV-8B improvements and designated YAV-8B. These aircraft employ vectored thrust to achieve vertical and short takeoff and landing capability with a modest weight penalty. The Pegisus engine is a high bypass ratio, turb-fan unit built by Rolls Royce which can provide 21,500 lb thrust with water injection. The engine bypass flow exits the forward nozzles. The core flow enters a plenum, is split, and exits through two aft nozzles. See Figure 2. The jet nozzles rotate downward from straight aft to 12 degrees forward of vertical as shown in Figure 3. This arrangement results in engine exhaust plume impingement on the airframe.

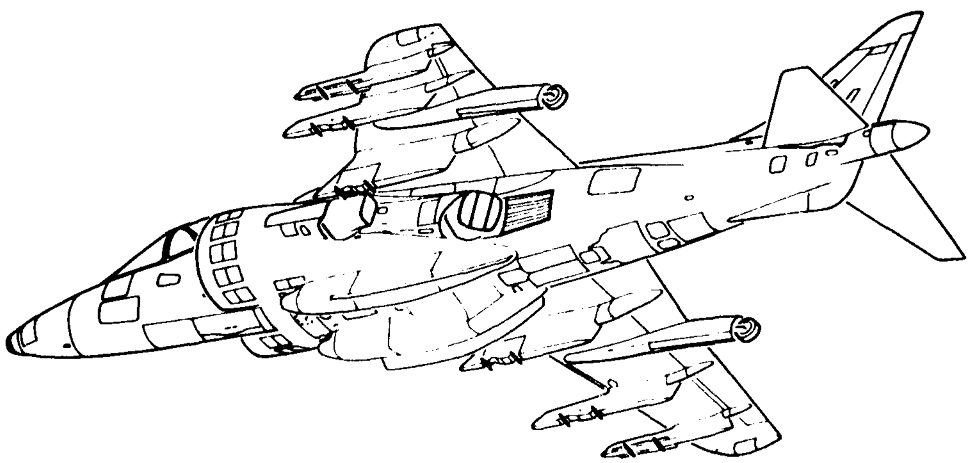

FIGURE 1
AV-8B AIRCRAFT

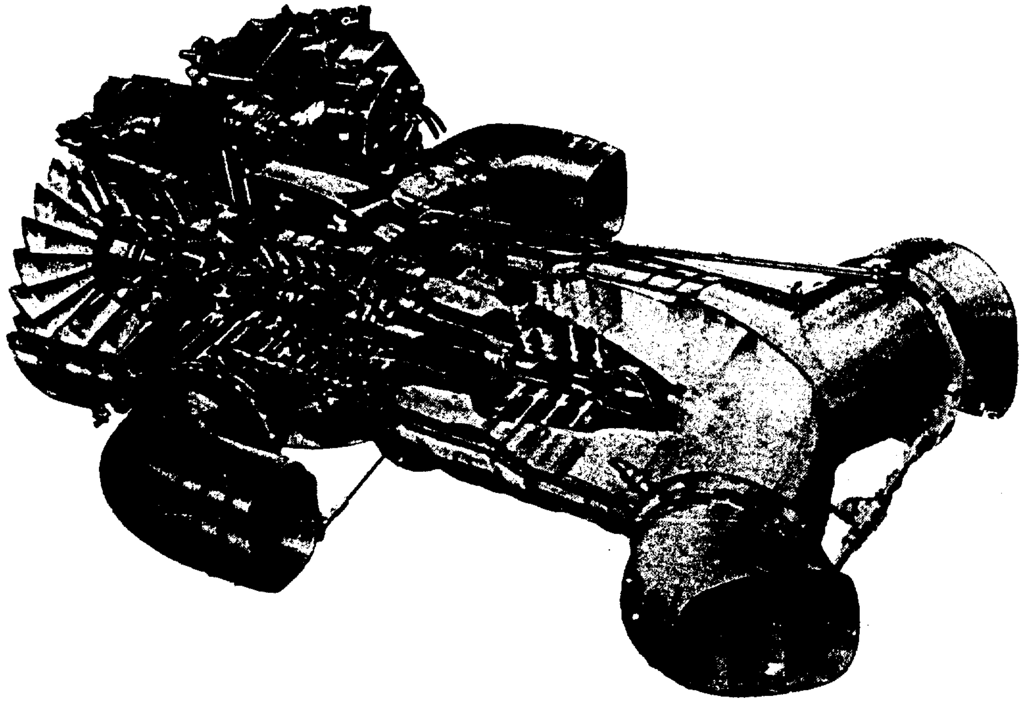

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FIGURE 2
ENGINE AND NOZZLE SYSTEM

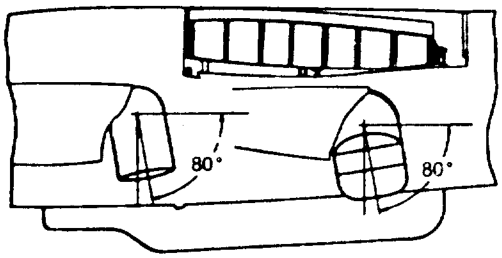

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FIGURE 3
NOZZLE IN HOVER POSITION

The AV-8B was built to U.S. requirements which would normally make MIL-STD-810C the governing document for equipment procurement. However, in order to minimize procurement cost, it was decided to use as much of the existing Harrier equipment as possible with minimum modifications. Items requiring no change that would compromise their existing functional behavior or environmental resistance were accepted directly under a "grandfather" agreement. Acceptable service use on Harrier was accepted as sufficient qualification. Most of this existing equipment had been procured in the United Kingdom under British Standard 2G.100 or 3G.100.

For new equipment or for items requiring extensive modification, the goal was to develop vibration requirements which would accommodate either MIL-STD-810C or B.S.3G.100 testing to the extent possible.

MIL-STD-810C AND B.S.3G.100 COMPARISON

A comparison of the two standards indicates some troublesome differences as indicated in Table 1. Both prefer wide band, random vibration testing, and attempt to relate endurance vibration test level/duration to a required fatigue life for the intended aircraft application. 3G.100 specifies fixed vibration levels for various flight modes and derives the test duration by equivalencing "time-in-condition" at lesser levels to a referenece level based on the 5'th power ratio:

$$\frac{T_{equiv}}{T_{ref}} = \left(\frac{S_{ref}}{S_{less}}\right)^{2.5} = \left(\frac{a_{ref}}{a_{less}}\right)^{5} \qquad (1)$$

810C uses an empirical equation based on the maximum dynamic pressure, Q, of the aircraft considered; the length of test desired; T; and the number of flights in the equipment lifetime, N. The random power spectrum level, W_o, is given as:

$$W_o = K\ Q^2 \left(\frac{N}{3T}\right)^{1/4} \qquad (2)$$

Here, K is specified for different zones in the airframe. Neither method provides satisfactory results for a vectored thrust aircraft as shown in the Appendix.

Item	MIL-STD-810C	B.S.3G.100
Preferred Vibration Test Type	Wide Band Random	Wide Band Random
Endurance Test Related to Fatigue Life	Yes	Yes
Derivation of Test Level	Calculated From Q and Time	Time Compression Using Specified Levels for Various Flight Modes
Frequency	15 - 2,000 Hz	10 - 1,000 Hz
Endurance Test Time	1 - 2 hr/Axis	15 - 50 hr/Axis
Separate Performance Vibration Test	Yes	No

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TABLE 1
COMPARISON OF U.S. AND BRITISH STANDARDS

The other significant difference is the variation on upper frequency limit for testing. This point will be discussed later.

UNIQUE CONSIDERATIONS OF AV-8B

The dominant vibration sources are engine related on AV-8B. In order to have a vertical life capability, the engine nozzle thrust must be balanced about the aircraft c.g. This results in direct exhaust plume impingement on the aft fuselage and empennage when the nozzles are directed aft, and ground-reflected impingement on the entire underside of the airframe when the nozzles are aimed downward. An appreciation of this variation in energy distribution may be obtained from the near-field acoustic plots of Figure 4. In both cases the engine is at full power with water injection. Table 2 indicates the variation in overall level at several airframe locations for these two conditions.

The small size of the AV-8B airframe and the C.G. requirements demand that much of the equipment be installed in the aft fuselage. Therefore, this high vibration zone cannot be avoided for installation of equipment including large electronics boxes.

The mid-fuselage engine position causes the inlet ducts to be very short. Also, the need to intake sufficient air for full engine power at zero forward speed requires the inlets to be quite large in frontal area. These two factors allow significant acoustic energy to be transmitted forward from the engine fan stages along the fuselage sides. The light weight composite structure transmits a significant amount of this energy as structural vibration to equipment installed in the forward fuselage.

THE AV-8B COMPROMISE

Initially AV-8B vibration predictions were made using the methods of 3G.100 and 810C, and were compared to measurements made on the earlier Harrier versions. This comparison indicated that neither method was successful as indicated in the Appendix. The approach used for AV-8B enployed the equivalencing scheme of 3G.100, Equation (1), based on overall levels from the Harrier measurements. These were expressed in Grms over a frequency range of 10 to 1000 Hz. The times for various flight modes were predicted from operational mission analysis for the required 6000 hour equipment life. The result was a reference vibration spectrum and an equivalent exposure time for each aircraft zone. For the aft fuselage example in the Appendix this amounts to 26 hr at 31 Grms.

It was decided to use the 3G.100 frequency range of 10 to 1000 Hz because few items have sufficiently rigid mountings to transmit structure-borne vibration at frequencies over 1000 Hz. Furthermore, acoustic testing can input more energy and cover this frequency range more efficiently.

Two performance vibration requirements were established. One was of five minutes duration at the highest of the levels experienced in the V/STOL mode including takeoff, hover, landing, and engine ground run. For items whose performance was of no interest during the operations, the V/STOL performance requirement could be waived. The cruise performance vibration requirement was based on the highest level experienced during wing-borne flight, and was of 25 minutes duration. This was sufficient time for a test level based on maximum Q flight. Cruise performance levels tended to be lower than V/STOL performance levels, but compared to the performance level concept of 810C. To accommodate the lack of a performance test in 3G.100, the entire performance test could be waived if satisfactory performance could be demonstrated during the endurance vibration test.

A choice of endurance vibration test requirements was offered to accommodate either 810C or 3G.100 customary practice. One of these specified a test duration of 3 hr/axis, and the other required a test duration of 16 2/3 hr/axis at a lesser level. Both test levels were based on a rearrangement of Equation (1), and the prediced equivalent fatigue life discussed at the beginning of this section. Here, T_t is either 3 or 16 2/3 depending on the level used.

$$\frac{(G_{rms})_t}{(G_{rms})_{ref}} = \left(\frac{T_{ref}}{T_t}\right)^{0.2} \quad (3)$$

Each should provide equivalent total fatigue energy, other considerations aside. Besides providing a choice of test more in line with one of the two Standards, two other benefits were realized.

1. Depending on the ruggedness of the test article, time in jeopardy during the test could be traded against the cost of test duration.

2. A test level could be avoided which might be higher than the fatigue endurance limit of the equipment structure.

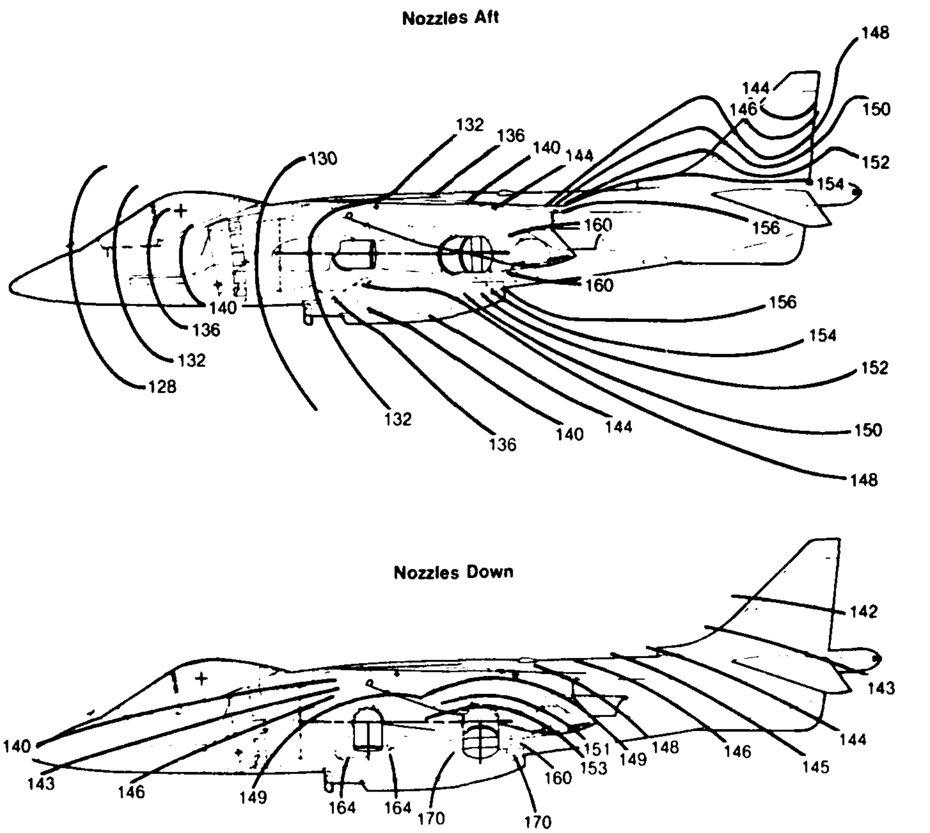

FIGURE 4
NEAR FIELD ACOUSTICS

Location	Nozzles Aft	Nozzles Down
Aft Fuselage	31	7
Center Fuselage	3.9	4.9
Forward Fuselage	3.4	6.1
Centerline Pylon	13	34

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TABLE 2
AV-8B OVERALL VIBRATION, G_{RMS}

OTHER CONSIDERATIONS

Care must be taken in elevating test levels by time compression to avoid transition to a regime of low cycle fatigue. This was the reason for setting the minimum endurance test duration to three hr/axis instead of the usual one or two hr/axis. A piece of equipment may endure a relatively high vibration environment for 6000 hours, but the extremely high levels resulting from time compression to a one hour test would exceed the fatigue endurance limit of the design's structural details. A weight penalty would result in the equipment design required to pass this test which would be unnecessary in surviving the service environment.

Throughout the AV-8B development a 5'th power equation was used. Other exponents can be found in the literature; 6.5 in particular. Besides its reference in 3G.100, other reasons exist for the use of a 5'th power ratio.

1. The s-N fatigue curve for aluminum is a 5'th power hyperbola, and most equipment structure is aluminum.

2. A 5'th power ratio is more conservative than higher powers because it gives more weight to lower vibration levels. The hyperbolic fits for steel, titanium, and composites have higher powers in a range of six to ten.

CONCLUDING REMARKS

A discussion has been presented which indicates how the unique vibration environment of a vectored thrust aircraft was incorporated in a compromise specification betwen the regimen of MIL-STD-810C and that of B.S.3G.100. The results were the vibration test requirements which were used in the procurement of AV-8B equipment. Listed, they are as follows.

1. Test type - wide band random in a frequency range of 10 - 1000 Hz.

2. Performance vibration test - two segments:

   a. V/STOL performance based on the highest level expected during this mode of operation for 5 min/axis. Test may be waived if specification performance not required in V/STOL mode.

   b. Cruise performance based on the highest level expected during wing-borne flight for 25 min/axis.

   Entire performance vibration test may be waived if specification performance can be demonstrated during the endurance vibration test.

3. Endurance vibration test. Either one of the following may be used:

   a. 3 hr/axis at a spectrum elevated by time compression from the reference equivalent fatigue life for the applicable aircraft zone.

   b. 16 2/3 hr/axis at a lesser spectrum similarly derived from the reference equivalent fatigue life.

Currently, the AV-8B has reached a cumulative flight time of over 25,000 hours in Marine Corps use. The individual high time aircraft have reached 1000 flight hours. The vibration test methods discussed herein have proven quite adequate based on fleet performance to data.

NOMENCLATURE

G	Overall acceleration level	G_{rms}
Q	Dynamic pressure	lb/ft^2
N	Number of missions per equipment lifetime	
S	Power spectrum level	g^2/Hz
T	Time	hr
W_o	Test spectrum level from MILSTD-810C	g^2/Hz
a	acceleration	

APPENDIX

Following are aft fuselage endurance vibration levels calculated by the methods of MIL-STD-810C, B.S.3G.100; and the method developed for AV-8B.

<u>MIL-STD-810C</u>
6000 one hour missions and a test time of 3 hrs are assumed. W_o is calculated at .72.

B.5.3G.100

The aft fuselage would be Region A, Category 4. Therefore, the test spectrum level = 0.02 and the test time calculated is tabulated below.

Mode	Time	Cat.	R*	Test Time
takeoff	18	4	1	18
buffett	25	3	.177	4.42
max power	73.5	3	.177	13.0
cruise	5280	1	.00056	2.96
				38.4

$$*R = \frac{S\ \text{less}}{S\ \text{ref}}^{2.5}$$

AV-8B METHOD

The calculation of an equivalent fatigue life is indicated below. The times in the second column are totals for 6000 flight hours.

One equivalent fatigue life = 1.53 (15.4) = 23.5 hr @ 31.2 grms.

$$*R_a = \left(\frac{\text{grms}}{\text{grms reference}}\right)^5$$

$$**R_t = \left(\frac{\text{total time}}{\text{total time, reference}}\right)^{R_a}$$

The three hour endurance test overall level becomes (Equation 3):

$$(\text{Grms})_t = 31.2\left(\frac{23.5}{3}\right)^{.2} = 47.1 \text{ grms}$$

The longer endurance test overall level becomes:

$$(\text{Grms})_t = 31.2\left(\frac{23.5}{16.7}\right)^{.2} = 33.4 \text{ grms}$$

Figure A1 shows the spectrum shape for these tests as well as those of the 810C and 3G.10 specifications.

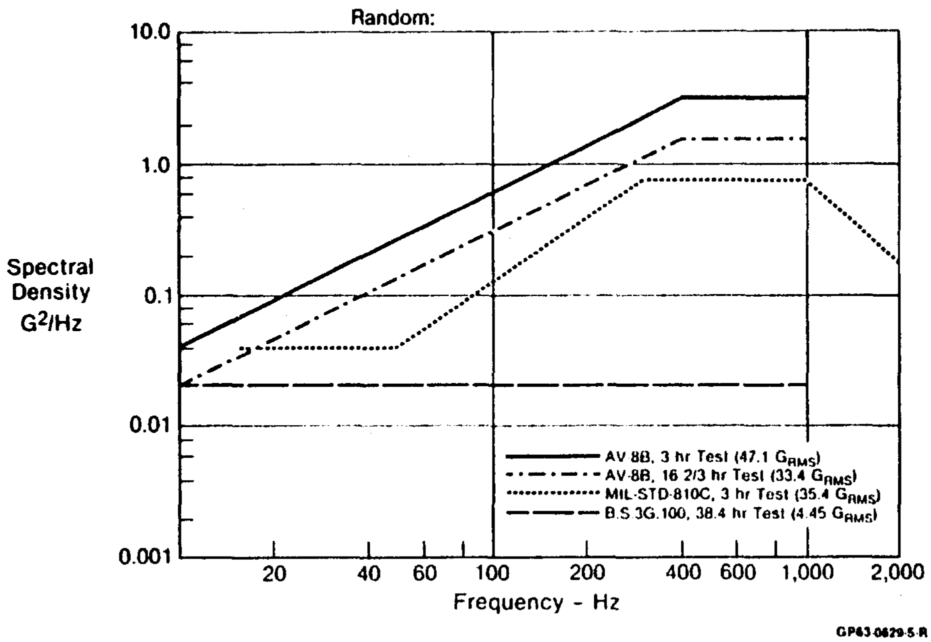

FIGURE A1

VIBRATION TEST SPECTRUM COMPARISON, ENDURANCE

AFT FUSELAGE EQUIVALENCE

Cond.	Total Time (hour)	Response (grms)	R_a *	R_t **
Gnd run	5	31.2	1.0	.325
NGVTO	0.5	11.2	---	----
taxi	500	0.8	---	----
STO	15.4	31.2	1.0	1.0
CTO	3.4	27.8	.562	.124
climb	416	7.4	7.5×10^{-4}	.020
cruise	4450	4.4	5.6×10^{-5}	.016
max power	73.5	10.4	.004	.020
buffet	25	11.0	.005	.009
descent	414	6.7	4.6×10^{-4}	.012
hover & VL	137	5.8	2.2×10^{-1}	.002
SL	137	6.5	3.9×10^{-4}	.003
				1.53

PYROTECHNIC SHOCK WORKSHOP*

DESIGNING ELECTRONICS FOR PYROTECHNIC SHOCK

Henry Luhrs
TRW
Redondo Beach, California

The following are comments made at a Pyrotechnic Shock work session. Experience with testing and designing spacecraft electronic equipment for pyrotechnic shock are described.

I would like to start by outlining my experience. Almost all the electronic equipment (black box) I have worked on our own spacecraft. Most of which are small rugged assemblies with no moving parts. The test levels that are imposed on these typical spacecraft electronic equipment range from a peak shock spectrum of 1000 g's starting at 1000 Hz up to 17,000 g's starting at 4000 Hz. The shock spectra for drop-tower shock tests for piece parts usually are in the 1500g to 5000 g range. I will talk about my experience in designing this type of equipment for these levels. The design spectrum and the test method, because the test method is just as important to me, if not more so, than the absolute level of the environment. I must design differently for a drop tower, for a "ringing plate" or for an actual pyrotechnic on a spacecraft, even for the same spectrum. The test method makes a big difference, whether I pass or fail the test, so the test level and the test technique must be considered together.

My experience in shock testing piece parts has been mainly with the drop-tower. I have not failed any piece parts such as transistors or flat packs up to shock test levels of 5000 g's. I therefore expect success in the 2500-5000 g region. But, relays and crystals are a different story; here failures usually begin to occur in the vicinity of 2500 g's so the 2500-5000 g area usually becomes a gray area. The lowest shock test level, however, where I have experienced parts failures was around 800-900 g's during a shock test on a relay. This gives you an idea of the region that I am concerned with. Most of the relays used in our equipment can withstand shocks up to 2500 g's; this is our standard relay. Twenty-five hundred g's is the beginning of a gray area where the shock resistance of shock designed relays and crystals becomes marginal.

My drop-tower shock testing experience with electronic equipment has been with fairly small units. Structural failures of the mounting feet have occurred in the region of 2500 g's. I, however, have not tested any large units to those high levels on drop testers.

I have also had considerable experience using a shaker as a shock simulator for units. In this case, no structural failures have occurred at 2500 g's on quite a number of units. However, crystals in a unit and a small microswitch with a gold bonded wire have failed at this level. In addition, numerous relay transfers have occurred in one unit, and a relay suffered some permanent internal damage. Therefore 2500 g's shock is the failure threshold for this type of spectrum using a shaker shock test. This raises the question what shock levels would units without these piece parts endure? I have tested units without these sensitive parts to levels of up to 5000 g's, at 3000 Hz, without any structural failures. This means the structural failure level was above 5000 g's at 3000 Hz. But 5000 g's at 3000 Hz works out to a number of approximately 1.5 using the velocity type frequency relationship, so I was up to a number of 1.5 without a structural failure, but I was just marginally failing crystals and other sensitive parts down in the 0.8 region.

I have also had experience testing on a structure which simulated the actual spacecraft structure. Everything passed at 2500 g's. I even had the same unit in this test that failed the 2500 g shock test on the shaker. I didn't even get relay chatter. In addition we have actual spacecraft test firing, where we fired the real pyrotechnic devices, e.g., bolt cutters, pin-pullers and the like, no failures have occurred at any time. Levels as high as 7000 g's have been measured near a TWT. Most levels however are well below the 2500 g TWT specification I had for the simulator. Overall therefore extrapolating from this experience I expect the failure threshold to be reasonably above the 2500 g peak.

Another technique was the "ringing plate". I have tested a few units up to 4500 g's without failures. I must point out however, that there were no sensitive parts in those units. The highest test level I have ever reached was 18,000 g's during a shock test on one unit. The only structural failure, if I can call it that, was some screws became loose after several test runs. I

*This paper was presented in the Pyrotechnic Shock Workshop at the 56th Shock and Vibration Symposium

didn't fail piece-part leads, circuit boards, or basic structure. Again there were no particularly sensitive parts. From this limited experience for our spectrum shapes structural failure of units seem to be above 4500 g's.

Why am I having this inconsistency in trying to develop my failure level? One answer is that one test method, for the same shock spectrum, is substantially worse than another. I therefore would have to compare the failure criteria against the test method. I believe that shock tests on a rigid fixture on a shaker, would, on a peak spectrum, differ in severity by a factor of approximately five. That is, if the failure level on a rigid fixture is 0.8 times the frequency then the same equipment would pass at a level of 4 times the frequency on a simulator or on a real structure. Failures might even occur at a lower level, 0.6 times the frequency, if the tests are conducted on a drop tester.

Next we should compare the test method and requirements with spacecraft flight data. For most tests we have enveloping techniques, margins are imposed, the shock wave is correlated at the mounting feet, and the test fixture or plate is fairly rigid. All of these differences produce a much more severe shock test than the actual spacecraft environment. As a result the actual margin is really higher than specifying agency thinks it is imposing. Likewise the design should consider these tests differences when evaluating the test damage potential.

Now to a new topic; How do I design the unit to resist pyrotechnic shock? First, I must recognize the basic failure mode. Lets review the structural failure mode first. I have not experienced any structural failures in the 5000 g region on a unit that was designed to resist random vibration levels at approximately 0.3 to 0.4 g^2/Hz at the first fundamental resonant mode of the unit. For example, on one program we have a shock specification of 4500 g's and a random vibration environment where the PSD is 0.4 g^2/Hz at the resonant frequency region of the unit. We will design the structure to pass the random vibration test, and we expect the same design to structurally pass the 4500 g pyrotechnic shock requirement. Our design criteria is to design for the random vibration, don't design for pyrotechnic structural loads.

Now let us consider the failure modes of transistors and diodes. I don't expect those parts to give me trouble, so nothing unique needs to be done. But, when relays, crystals, or switches are present, I begin to worry, and I don't trust a 4500 g level. In this case failures might be avoided by selective use of available parts and by providing out the available parts with their own special shock tests. In the past we have had to use parts for electrical reasons, and we did not find their shock resistance was acceptable hand mounted. We therefore, as one example, have isolated those parts, e.g., crystals and big power relays within the unit itself. We have developed compliant mounting for alumina substrates. They are shock resistant to above 5000 g's.

This is another possible failure mode. The position accuracy of frictionally held items can be affected. (After yesterday's talk I will refer to this as the zero-shift problem). Parts held in place by friction, such as a helix in a traveling wave tube, can shift, and they will detune the circuit. This is similar to the failure mechanism with accelerometers discussed yesterday. The sock range where this occurred in my experience was 2500 g's or above.

To summarize my comments, I do not feel most of my problems with failures are true shock design problems. In jest it can be said "there is nothing wrong with this unit that a change in spec would not fix". For most of my designs, as far as structure is concerned, I design for random vibration and I will structurally pass the shock tests. Next, we must get to the electrical engineer to design out electrical performance failure mechanisms if possible. An example would be to allow a relay to chatter without it being a failure. A crystal can have some noise without it being a failure. Fortunately these piece part abnormalities are not normally failure mechanisms for spacecraft because in the application of that equipment most of the equipment does not need to function during shock.

We also often work with the manufacturers of crystals, relays, and the like, to modify parts so that they can pass the environment.

Frequently the part specification does not give the true fragility of the part, but is only indicative of the test level verified. As an example, we had one relay especially designed for us, which was modified from an existing design. The manufacturer maintained the identical specification and just changed the number. We now have two different parts, with the same basic electrical and mechanical specifications, but substantially different capabilities. We have found by our own tests that there can be a big difference between parts, which is information we use in design. In some cases, we have had to shock isolate parts when we have not been able to get the parts up to the level we want. There are however limitations to isolation systems. These include, unacceptable change in crystal electrical characteristics, increased thermal resistance, and volume limitations. When we must isolate we have almost exclusively, isolated the one part within the unit itself, and not the whole unit.

There are other design techniques which I also use. As an example; I have gone the route of making my structure and using as many joints as I can to get up to critical part.

If friction is important to the performance of the part, then we try to eliminate as many frictional joints as we can by bonding or some other kind of locking device that can hold the part in place. And finally, when we work with the spacecraft layout, those units which we expect to be shock sensitive, we try to locate them further from the shock source. Our shock source, in almost every case is a point source, not the zipper type so we have been able to take advantage of preferred locations to some degree. This effectively completes the comments I've prepared for this presentation. I however would also like to address some of the points made by Chuck Moening of Aerospace this morning.

Chuck stated that a comment made by contractors is "The shock environment is too short to cause failure, a three minute vibration test is more severe". I'd like to relay my experience. For my shock tests I've not had structural problems, but there are other potential problems such as relays or crystals, therefore the statement is partially true.

The next comment he hears from contractors is "Our electronic equipment will be reduced to scrap, if exposed to pyrotechnic shock levels of several thousand g's". My response is I expect typical spacecraft equipment to be capable of meeting shock levels on actual spacecraft structure, exceeding 5000 g's. I expect I can also get up to 5000 g's without failure on "ringing plates" used for unit testing.

The next contractor statement Chuck has received is "The predicted shock levels are much too high or too low". Yes, definitely, both are true sometimes. Another comment from contractors is "Avionics equipment doesn't fail at shock levels below 1000 g's. We are wasting money testing equipment to such levels. Let's delete the test required." My comment is, possibly, if you are judicious with your use of that statement. If you have designs which are tested to reasonable random vibration levels and that do not have the shock sensitive parts, or if you have instituted a program to test those parts, and just select those parts which will survive, then I believe that the statement would be true. Experience is that when these criteria are met then testing the unit at normal 1000 g's spectrum have not given me any information.

The next contractor statement that Chuck has received is "We have never had a flight failure due to pyrotechnic shock, let's delete the test requirement and submit a cost savings". My comment is, Yes, if you have done the proper steps ahead of time and on a selective basis, then I think you can delete some shock test requirements on select programs and on selected types of units. But, not across the board! There are potential shock design failure modes such as relays or crystals. Another failure Chuck discussed was contaminants, and the third area was the wire leads and the cracked glass. Chuck also said these occur at shock levels in the range of 3000 and 6000 g's. We however have not experienced any failures of wire leads at this level. I don't have experience with glass, but relays and crystals have failed in this range.

The problem with contaminants, is an interesting one. I don't look at contaminants as a shock failure problem, I don't even like to have it in the same category. This is a workmanship problem and a parts problem; its not a unit shock design problem. I have run into this problem a number of times. We therefore must combat the problem in assembly and not by a qualification shock test. Shock, however can be useful in acceptance testing, but only as part of a series of tests where vibration follows shock. The unit then must be monitored for intermitents during vibration to determine if the shock broke a contaminant lose.

Mr. Moening: Is it your standard practice to use passivatived parts?

Mr Luhrs: Passivation is good practice and is used any and every place where the electrical performance allows it. There have been cases where the electrical performance has not allowed it. I did have one case where a passivated part failed. Two leads coming into the part were so close together that even a small contaminant was able to short across the leads even though we had passivated it.

Mr. Windell (Admiralty Research Establishment): I am having a problem with your statement as I understand it, that the test methods supposedly had normally the same spectrum. When you say spectrum you are talking about the shock spectrum. Have you taken into account that the shock spectrum ignores the phase, it throws away phase information? Did your different tests actually have different phase relationships? Was that why you were getting different failure modes?

Mr. Luhrs: You have input phase relationships. When I perform tests on a rigid structure, all of the feet are correlated and the inputs are correlated. When I test on the "ringing plate" I do not have input phase correlation, I do not have the same environment at the same time, I do not have the same impedance matching. So these differences mean that the effect of that shock is different for different test techniques although "I have met the "spec".

Mr. Windell: I would just like to suggest there is a different spectrum involved.

Mr. Luhrs: I have discussed that with Chuck Moening on more than one occasion. We never came to an agreement on that one.

Mr. Windell: You have spoken about the failure of component parts, relays and the like; in general did the failures correlate with resonant frequencies of the component parts?

Mr. Luhrs. On the relay, yes. On the crystal, no. The crystal was a brittle fracture, so I would say that it is reacting to the very high frequency ring. The relay has a yoke going around it to support the mechanism. It is that resonant frequency mode that causes the failure. When it rings, it causes motions, and the contacts chatter.

Mr. Van Ert (The Aerospace Corporation): I know TRW is one of those people who use this practice; there is a list called the Program Approved Parts Substitution List. Are those parts that can be substituted without supposedly altering the qualification status of the hardware? Are those parts tested, or is there some way of their being validated so that we know we are not substituting a shock sensitive part for a non-shock sensitive part?

Mr. Luhrs: We selectively put the pyrotechnic shock test requirements on relays, crystals, and the like. We do not do it now across the board. As an example, small capacitors and resistors, generally speaking, do not have a pyrotechnic shock requirement. I therefore can substitute parts, which are sensitive, where both have been tested. Parts which are not sensitive are not tested therefore can also be substituted since there is no concern with their capability.

Mr. Silvers (Westinghouse): We are very interested in that comment you made about losing the battle if you get loose particles inside your integrated circuits or components. I think you said, by some sort of procedure, either a sampling procedure, or a qualification procedure, you could assure yourself you didn't have this type of workmanship problem. What is that procedure?

Mr. Luhrs: We have a process control on the parts along the line. On the critical parts we have had the passivating approaches. We have had our QA people do open lid inspection. We also have lot inspection. So it is a matter of putting extremely tight controls on the fabrication techniques of those parts to assure that they don't end up a contaminent problem. On select parts we have PIND testing. So it is a combination of these steps together to get us to the point, of eliminating contaminents.

Mr. Silvers: But you do not universally PIND test your integrated circuits.

Mr. Luhrs: I know we do it selectively on parts, and I am not really sure of which ones. I know, as an example, we had at least one that we wished we had PIND tested, and later had to purge from assembled units. The other lesson I learned from this is the type of problem is that the electrical testing that is done to meet the functional requirements may not be adequate to catch contaminants. Because the failure mechanism has a very short time, and if it occurs in a part its a short blip which is hard to detect.

Mr. Silvers: In our experience when we looked at MIL-STD-38510, Class B primarily, we would find a fairly large amount of metal particles inside. A rather scary percentage of them were S level parts, and it was my opinion they were all PIND tested, which would be for spacecraft.

Mr. Luhrs: I know on one of the programs I am working on now have S level parts.

Mr. Silvers: Most of those parts are passivated. I agree with you that you have lost the battle trying to get them at the system level because those particles tend to be pretty small, and they attract to surfaces in one way or another. And, if you ran them by a box trying to get that you would get some failures, and you might get two percent of the ones that might happen.

Mr. Luhrs: In our case there were 20 units that had this suspect part in it that got through the standard acceptance testing without showing the failure. Then we tested just for finding a particle, aimed only at hitting that particular problem, and we found three units that had gotten through. Finding this problem in a unit or system is extremely difficult, therefore the effort must be at the part level. I unfortunately have seen it occur on the unit level. We have developed techniques to test at the unit level, however they are costly and time consuming.

Mr. Silvers: The particles we say that really worried us were the eutectic gold bonds of the dies. That was the systematic problem we saw.

ZEROSHIFT OF PIEZOELECTRIC ACCELEROMETERS IN PYROSHOCK MEASUREMENTS*

Anthony Chu
Endevco Corporation
San Juan Capistrano, California

Zeroshift, a common measurement error in piezoelectric shock accelerometry, is any spurious output baseline shift which occurs after a pyroshock event. In this paper, all components of the shock measurement system are analyzed for sources of zeroshift, and preventive practices are presented to aid in equipment selection, setup, and operation.

INTRODUCTION

In acceleration data, zeroshift refers to any spurious baseline shift which occurs in response to a transient acceleration. This effect has been documented since the early 1950's. In 1971, Plumlee [1] and Davis [2] of Sandia Corporation published technical studies in which contributions to zeroshift from high-g shock effects in the ferroelectric ceramics were examined at great length. These reports, however, did not treat the contributions of other sources in the total measurement system. Recently, Schelby [3] published recommendations for measuring high-level, short-duration shock waveforms, and summarized them into an overall system specification.

Early research at Endevco indicated that zeroshift effects can be created in the accelerometer, the cable, and/or the electronics. This paper presents the results of a recent reevaluation of zeroshift causes, considering all the components of the measurement system. The study indicates that, in addition to effects within the ferroelectric material, other sources such as slippage of internal parts, cable noise, straining of sensing element, inadequate system low frequency response, and overloading of electronic circuits can also lead to zeroshift. This paper shows that, for most shock measurements, zeroshift can be minimized or eliminated through proper component selection and instrumentation system setup.

BACKGROUND

High level transient acceleration or shock response of an object under test is commonly measured by a piezoelectric accelerometer, which converts sensed motion into electrical signals for recording and analysis. Any differences between the accelerometer output and the actual input acceleration represent errors which may invalidate the test results. Zeroshift is commonly defined as failure of the electrical output of a piezoelectric accelerometer to return to its original zero baseline after an acceleration transient. This shift can be of either polarity and of unpredictable amplitude and duration.

Samples of two similar acceleration-time histories are shown in Figures 1A and 1B. Figure 1A shows an accurate measurement of a pyroshock event, with a maximum amplitude of about 50,000g peak. The high frequency ringing is superimposed on a baseline which is unchanged from the preshock level. Figure 1B shows a similar pyroshock waveform, but the high frequency components are superimposed on a baseline which has shifted by nearly -40,000 g from the preshock level. The step change in output in Figure 1B appears to indicate that the test specimen has suddenly experienced a constant negative acceleration of 40,000g. Such large zeroshifts are normally detected during the test run and recognized as spurious because they represent impossible accelerations. Correction of the problem and retest, however, can be a costly undertaking and can result in unintentional overtest of the specimen. Lower levels of zeroshift often go unnoticed and create errors in subsequent data processing. Integrating an acceleration-time history with zeroshift yields unrealistic velocity and displacement results, and zeroshift can introduce errors in the low frequency portion of the shock response spectrum. Compensating for zeroshift requires making assumptions and interpretations, which can then be the source of unacceptable errors. The best approach to the zeroshift problem is prevention.

*This paper was presented in the Pyrotechnic Shock Workshop at the 57th Shock and Vibration Symposium

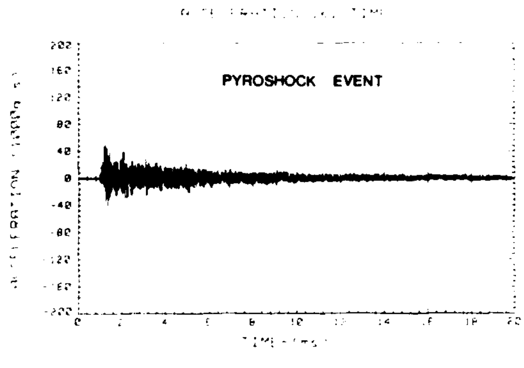

FIGURE 1A PYROSHOCK TIME HISTORY

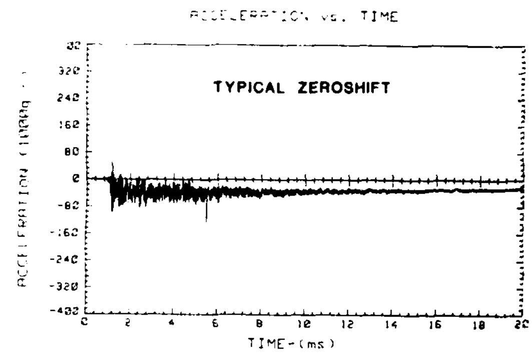

FIGURE 1B TYPICAL ZEROSHIFT

CAUSES OF ZEROSHIFT

Efforts to prevent zeroshift must be based on an understanding of all causes of zeroshift. In this study, each known cause of zeroshift has been separately investigated, insofar as possible. Testing was conducted using shock wave generated by Hopkinson bar, hammer drop, and flexible charge (pyrotechnic) cord. The causes of zeroshift that were investigated are:

(1) Overstress of sensing elements,
(2) Physical movements of sensor parts,
(3) Cable noise,
(4) Base strain induced errors,
(5) Inadequate low frequency response, and
(6) Overloading of signal conditioner.

A detailed treatment of each cause of zeroshift is presented in the following sections. In some instances, there are component choices or system configurations which minimize or eliminate a particular cause of zeroshift. Experience has shown, however, that no one cause dominates as a major source of zeroshift. Therefore, to minimize the actual zeroshift in a given test, all of the causes must be minimized or eliminated.

1. Overstress of Sensing Elements

The piezoelectric materials used for the sensing elements in acceleration transducers may be divided into two basic classes; ferroelectric ceramics (such as Lead Zirconate Titanates and Bismuth Titanates), and single crystals (such as Tourmaline and synthetic and natural Quartz).

Ferroelectric materials are made up of many individual crystaline regions or domains, hence the term polycrystalline ceramics. These individual domains are piezoelectric, but are randomly oriented after the material is formed. To produce a usable piezoelectric effect, it is necessary to align the majority of domains so that their piezoelectric axes point in the same direction. This polarization process is typically performed in a strong electric field, and is analogous to the magnetization of iron in a magnetic field [4] [5]. In a well-polarized and stabilized ferroelectric ceramic, piezoelectric charge output is linearly proportional to the amount of tension or compression in the material. However, if the element is overstressed, some of the polarized domains will switch back to their original positions, generating spurious additional output. These switched domains will eventually return to their former positions and as a result, produce no detectable sensitivity change in the accelerometer.

Because piezoelectric accelerometers normally have amplification factors (Q) well over 30dB at resonance, resonant ringing in response to pyroshock inputs will often cause higher element stresses than expected. The resulting domain switching [6] will generate zeroshift. Ferroelectric accelerometers with high effective mass and low resonant frequency are particularly susceptible to this effect.

The amount of domain switching due to a given stress during a transient acceleration depends on the formulation of the ferroelectric material, its polarization processing and its post-polarization stabilization, the pre-stress on the ceramic element, and the ambient temperature. Experiments [1] [2] have shown that the domain orientation seeks a new equilibrium condition for every new combination of stress, E-field, and temperature.

There are two broad classes of ferroelectric ceramic formulations, which differ in their polarization characteristics.

Low Coercivity materials, such as Lead Zirconate Titanates, which polarize at relatively low voltages. These materials also have high charge coefficients (charge/stress) which result in accelerometers with high output sensitivity. When subjected to a strong mechanical impulse or temperature transient, however, these materials exhibit domain switching rather easily, causing zeroshift at the output.

High Coercivity materials, such as Bismuth Titanates, which require a much higher polarization potential (usually three to four times that of low coercivity materials) to align the crystal domains. These ceramics are much more stable under a wide range of environmental conditions. Consequently, high coercivity materials exhibit considerably less domain switching than low coercivity materials at the same stress/field level. The low charge coefficient, however, limits the output sensitivity of the seismic system, and the low signal level may be more susceptable to other causes of zeroshift, such as cable motion. Most of these effects can be eliminated by using high coercivity material in conjunction with built-in electronics.

Single crystal materials, which include natural quartz, synthetic quartz, tourmaline, etc., do not exhibit the problem of domain switching due to the entire element being one crystal domain. However, since natural crystals cannot be shaped to achieve optimum configurations for use in accelerometers, they are only produced in configurations which are susceptible to other causes of zeroshift, as described below.

2. Physical Movements of Sensor Parts

The stress on the piezoelectric element of an accelerometer is created by the reaction of a seismic mass to the input acceleration. Obviously, any slippage between the mass and the element will result in an output error. In addition, if the accelerometer design utilizes a preload on the piezoelectric element, any slippage will result in the material not returning to its original preload. This step change in preload will show up as a spurious step acceleration on the transducer output.

Current piezoelectric accelerometer designs utilize a variety of construction techniques to support the sensing elements. Some of these designs are intrinsically more complicated than others, and consequently have more internal moving parts. Figure 2A and 2B depict the components of two common shock accelerometer designs.

Figure 2A shows a compression type shock accelerometer, in which preload is required for the crystal to produce linear output in tension. The preload is usually provided by some form of threaded stud in the assembly. When the unit experiences high-g shock, the stress wave travels through the base into the seismic assembly, and the tension portion of the wave can exceed the clamping force. In this relaxed condition, minute relative movements can occur between adjacent components. These slippages can result in spurious output which appears as zeroshift. In applications where the shock wave can impinge on the accelerometer from an off-axis direction, the preload compression construction is even more vulnerable.

Figure 2B shows an annular shear type shock accelerometer, in which no preload is required. The ferroelectric ceramic is secured to the transducer base (and to the seismic mass, if used) with high strength epoxy. This type of design is inherently free from parts movement unless the survival limit of the accelerometer is exceeded. It is equally robust to shock waves impinging from any direction.

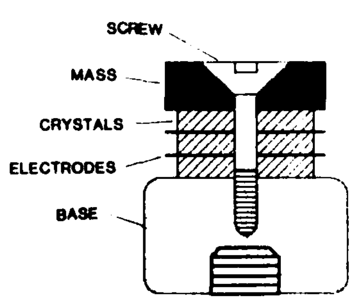

FIGURE 2A COMPRESSION DESIGN

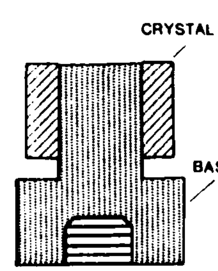

FIGURE 2B SHEAR DESIGN

3. Cable Noise

The direct piezoelectric output of an accelerometer is generated at high impedance, and generally requires the use of coaxial cable for its shielding and constant capacitance characteristics. However, because the output signal is at low amplitude, the coaxial cable itself can be a source of zeroshift. A poorly supported cable can flex sufficiently to produce spurious signals during high-g shocks. This noise generating mechanism is known as the triboelectric effect [7].

When a coaxial cable is physically distorted, as shown in Figure 3, a localized separation between the cable dielectric and the outer shield around the dielectric may occur. As the outer shield separates from the dielectric, the steady state charge distribution becomes unbalanced at the interface. Charges on the dielectric are trapped due to its low conductivity. Charges on the shield, however, are mobile and are neutralized by flowing to the center conductor through the input impedance of the electronic amplifier. This momentary current flow is sensed as a signal by the amplifier input. When the cable distortion is relieved, dielectric and shield are joined together and the formerly trapped electrons now flow into the shield, resulting in a second pulse of opposite polarity.

A typical cable motion induced zeroshift is shown in Figure 4. This experiment was conducted on the Endevco Compression Wave Shock Calibrator with a half-sine input pulse. A high-quality coaxial cable connected the high impedance accelerometer to the charge amplifier. Since the cable was allowed to flex during the shock event, spurious output was generated which appeared as a zeroshift.

4. Base Strain Induced Errors

Base strain or base bending sensitivity is defined as the output from an accelerometer caused by deformation of the surface to which it is mounted. This effect can cause a zeroshift error in some transducer designs. Compression accelerometers require preload for their operation, and usually display a high sensitivity to base strain. In addition to this direct base strain output, it has been demonstrated that mild strain (less than 250 micro-strain) can vary the preload and allow internal part movement which results in a sizable zeroshift.

To demonstrate this effect, several compression and shear accelerometers were tested. Each transducer was mounted near the fixed end of a long steel beam of rectangular cross section. (The details of this apparatus is described in the ISA tentative recommended practice ISA-RP 37.2, Section 6.6.) The units were mounted at their specified mounting torque, and the associated electronics was DC-coupled where possible. The free end of the beam was deflected to produce a 300 micro-strain impulse at the transducer location, as measured by strain gages. The strain step input was maintained for 0.5 second, which created a negligible acceleration at the mounting location.

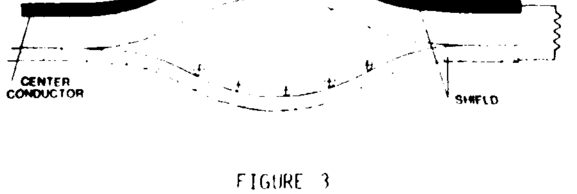

FIGURE 3
TRIBOELECTRIC EFFECT

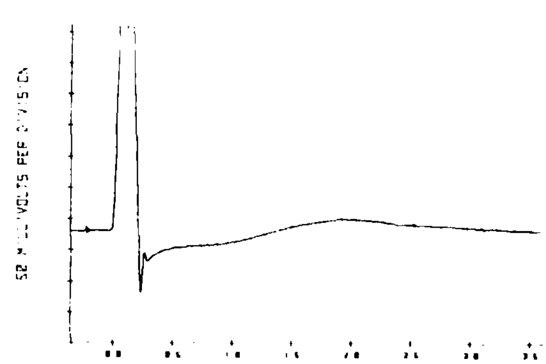

FIGURE 4
ZEROSHIFT DUE TO CABLE MOTION

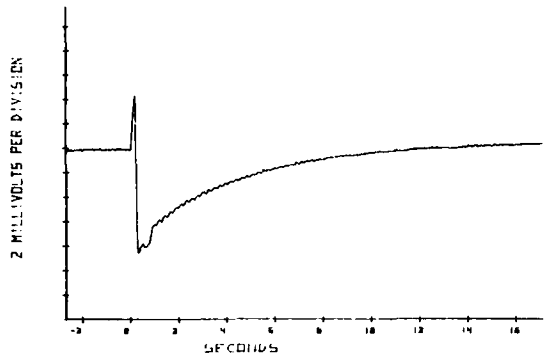

FIGURE 5A
COMPRESSION DESIGN UNDER STRAIN

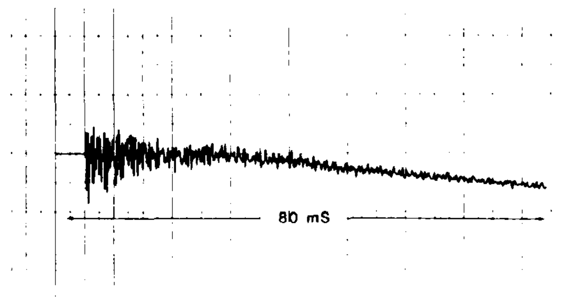

FIGURE 6A

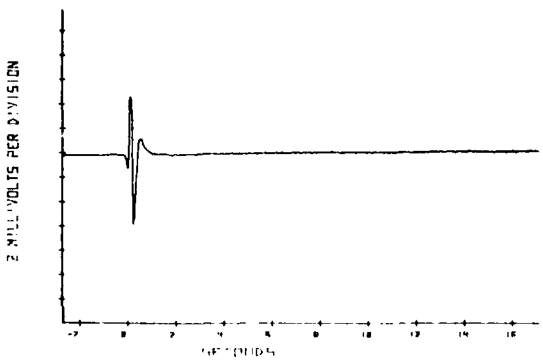

FIGURE 5B
SHEAR DESIGN UNDER STRAIN

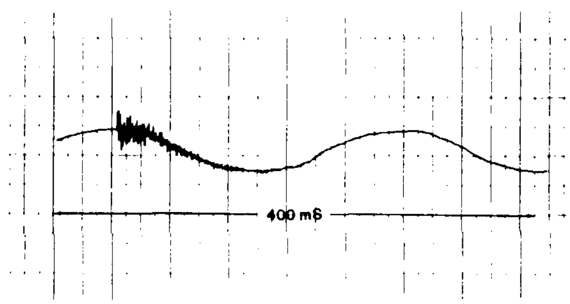

FIGURE 6B

Figure 5A shows the output from one of the compression (single crystal Quartz) accelerometers and Figure 5B shows the output from one of the shear (Ferroelectric) accelerometers. Momentary strain outputs were apparent on all units, as indicated by the spikes. The compression accelerometers also produced noticable amount of DC shift after the transient, however. This DC offset returned to zero following the RC time constant of the electronic signal conditioner. The shear accelerometers recovered immediately from the momentary transient, and no hysteresis effect was detected after the transient.

An accelerometer which produces a base strain output within its specification, and is free from DC offsets due to base bending, can nonetheless generate an output which resembles zeroshift. A shock event may contain low frequency bending waves, which may take a long time to die out. A base strain sensitive accelerometer will superimpose a signal due to this low frequency bending input upon the normal pyroshock acceleration signal. Because flexural waves can be at very low frequencies, the resultant data is usually mistaken for zeroshift, even though the accelerometer is operating within its stated specification.

Figure 6A shows the time history of a shock event with a viewing window of 80 milliseconds. By looking at the last portion of the shock recording, one may easily conclude that the transducer has zeroshifted. However, if one were to look at a longer viewing window, as shown in Figure 6B, it is obvious that the shock time history is superimposed on some low frequency signals. These base strain induced low frequency components can be at times larger in amplitude than the real shock data, confusing the operator during data reduction.

5. Inadequate Low Frequency Response

Zeroshift can also be created in the associated electronics. Inadequate low frequency response will result in failure to accurately reproduce the shock pulse. The nature of this distortion can be shown in Figure 7, which shows the theoretical response of an amplifier to a halfsine input pulse. The set of curves indicates the effect of varying the ratio of the RC time constant to the duration of the half-sine input.

As the time constant to pulse width ratio is reduced, amplitude error and post-transient offset become significant. This offset, or "undershoot", is opposite in polarity to the applied pulse. This type of zeroshift is usually associated with low frequency measurements, such as ground movements from explosion, where the pulse is assymetrical and long in duration. Sine-wave frequency response measurements may not provide a valid indication of the low end characteristics of a shock measurement system. For example, a shock calibration system which measures -3dB at 1Hz in a sinusoidal test might exhibit a significant amount of amplitude distortion and undershoot when subjected to a 100 mS half-sine pulse.

6. Overloading of Signal Conditioner

The spectrum of a pyroshock event may contain frequencies far above the passband of the measurement system. This undesired mechanical input can generate signals with higher amplitudes than those in the passband, causing the electronic circuitry to overload. This problem is aggravated by the effect of accelerometer resonance. Although most shock accelerometers have their resonant frequencies above 100 kHz, they can still be excited by pyroshock inputs. These inputs are amplified by the mechanical Q of the seismic system, resulting in very high, out-of-band electrical signals. When a signal conditioner attempts to process this signal, one of its stages is driven into saturation. No only does this clipping distort the in-band signals momentarily, but the overload can partially discarge capacitors in the amplifier, causing a long time-constant transient.

Figure 8 shows the output of a charge amplifier under overload conditions. The output exhibits undershoot which is determined by the discharge rate of its feedback capacitor and resistor when overloaded with an asymmetric input pulse. The severity of zeroshift of a particular signal conditioner depends on its clipping characteristics (whether it reacts equally to positive and negative inputs), recovery time, and the nature of the acceleration signal.

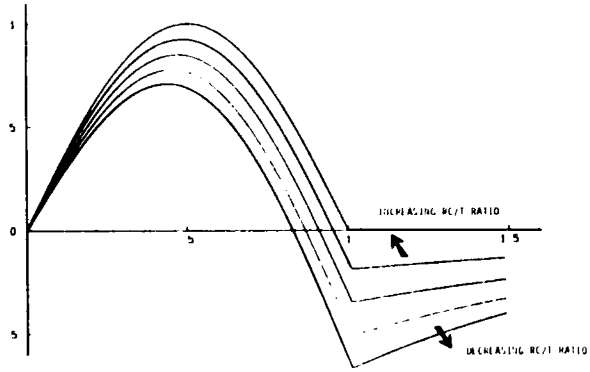

FIGURE 7
ZEROSHIFT DUE TO FREQUENCY RESPONSE

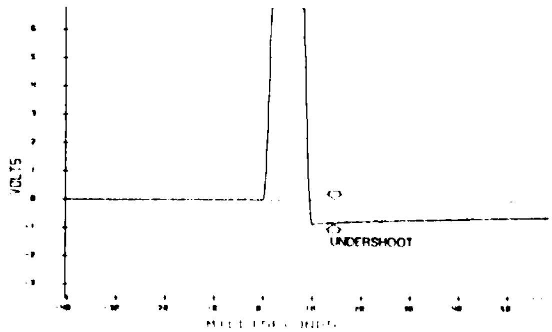

FIGURE 8
ZEROSHIFT DUE TO OVERLOADED ELECTRONICS

GUIDELINES TO MINIMIZE ZEROSHIFT

Since the various sources of zeroshift can generate a similar signature, it is extremely difficult to solve zeroshift problems by inspecting the output data. Therefore, all feasible precautions should be taken against each potential cause of zeroshift. Suggested guidelines are provided in the following paragraphs.

1. Transducer Design Considerations

   Avoid using shock accelerometers with elements of low-coercivity ferroelectric ceramics, to minimize domain switching (avoid Lead Zirconate Titanates).

   Avoid using shock accelerometers that use piezoelectric elements in a bolted preload configuration, to minimize physical movement of sensor parts (avoid compression design, which include all single crystal accelerometers).

   Choose accelerometers which have the highest resonant frequency. The higher the resonant frequency, the harder it is to excite the ceramic, hence less crystal domain switching. Transducers which utilize the weight of the crystal itself as the seismic mass reduce the effective stress even further and are, therefore, highly desirable.

   Shear type, high-coercivity ferroelectric accelerometers with minimum effective mass are recommended for pyroshock measurements.

2. Signal Transmission Considerations

   Use low impedance accelerometer designs which feature built-in impedance conversion. They provide:

   a) Reduced noise pick-up -- with low output impedance, the output signals are less susceptible to external noise sources when traveling through the long transmission line.

   b) Elimination of the coaxial cable -- regular hook-up wires can be used in place of coaxial cables because signals are low impedance. Hook-up wires are generally less expensive and more manageable than coaxial cables. In addition, hook-up wires does not exhibit triboelectric effect under motion as with coaxial cable.

   c) More options in connector design -- a bulky, shielded connector can actually induce strain to the sensing elements and produce spurious output. Simple arrangement such as solder pins will reduce the possibility of strain, plus have the advantage of field repairability.

If high impedance transducers must be used, great care should be taken when installing the connecting coaxial cable. It has been demonstrated that flapping and flexing of coaxial interconnects can generate zeroshift like signals. Therefore, it is necessary to prevent the cable from moving. Taping or gluing the cable on the mounting surface is highly recommended. Since the cable essentially experiences the same shock level as the sensor, miniature shielded interconnects should be used to reduce the moving mass under high-g acceleration. Noise treated coaxial cables should be used to minimize triboelectric output caused by cable motion. Consideration should be given to strain relieving the cable at the accelerometer, especially top-connector models (see Figure 9).

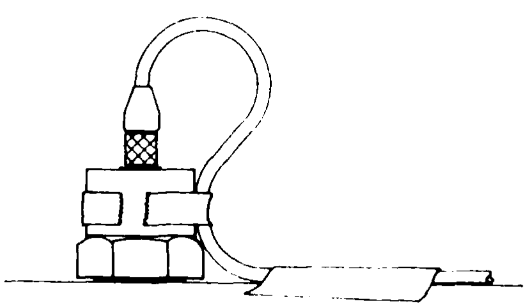

FIGURE 9
CABLE MOUNTING FOR MINIMUM STRAIN

3. Base Strain Considerations
Avoid compression type accelerometers if the mounting surface is suspected to have high strain. Base strain sensitivity is tested at fairly low strain levels, and is normally quite non-linear with strain levels. While the base strain specification of a compression design may seem acceptable, extrapolation to the expected test levels may not be valid. Accelerometers with the lowest possible strain sensitivity should be selected to provide the maximum margin against base strain errors. Furthermore, above a critical level of strain, a compression unit may produce zeroshift due to variations in the preload. Shear designs that do not require crystal preload are a better choice in high strain environment.

Shock accelerometers that incorporate base strain isolation in their design can effectively reduce strain motion to the sensing elements. This is presently accomplished by allowing sufficient clearance around the crystal assembly which concentrates the stress at a non-critical location. Correctly design, strain isolation groove and channel will not lower transducer resonance.

Another base strain reduction method is to use external isolator. Shaped like spacers and washers, these devices isolate the accelerometer from the mounting surface mechanically and minimize effective strain to the sensor. However, external isolators usually alter the resonance of the transducer which is not always desirable.

A longer time recording of the shock event will enable the user to distinguish real zeroshift from low frequency bending signal due to base strain sensitivity of the accelerometer. If this problem occurs, a lower base strain sensitivity accelerometer must be selected.

4. Frequency Response Considerations
All signal conditioning circuits should have sufficient time constant for handling long duration shock pulses, to avoid distortion related zeroshifts. As a rule of thumb [4], for a half-sine long duration pulse, the time constant to pulse width ratio ought to be at least 7 to obtain 5% accuracy. Low end frequency response of the signal conditioner should, therefore, be determined based on the input pulse width and output accuracy. Subsequent electronics, such as digital oscilloscope and waveform analyzer, should also be compatible in low end response. Attempting to use high pass filtering to remove zeroshift actually compounds the problem due to low frequency distortion.

5. Overload Considerations
To prevent electronics overload due to seismic resonance, a low pass filter may be employed before the very first input stage. Placing a low pass filter after the input stage may not prevent zeroshift because saturation can have already occurred. A shock accelerometer with built-in input low pass filter and impedance converter seems to be a logical solution [3]. Filter type should be carefully chosen to avoid excessive ringing, phase shift, and distortion due to group delay [8]. Select appropriate roll-off corner frequency to reject only unwanted information.

Select accelerometer sensitivity to suit a particular application; use lower output devices for large dynamic range. For safety measure, a factor of 2 should be used when estimating maximum acceleration level. When making measurement for one-time (non-repeatable) event, use two or more accelerometers of different ranges to allow for unexpected results.

For transducers with integral electronics that operate in constant current mode, increasing compliance voltage (within specification limits) will allow more headroom (swing) in the positive direction.

A MINIMUM ZEROSHIFT SHOCK ACCELEROMETER

One approach to an optimal shock accelerometer is shown in Figure 10.

Ideally, the sensing element should be inherently free of domain switching effects, and be used in a simple design which does not require preload. At the present state of the art, however, such a device is not available. An accelerometer which demonstrated the least amount of compromise in performance used high coercivity ferroelectric ceramics in the shear mode with minimum effective mass. Surrounding the sensing element is a strain isolation groove to minimize base strain errors due to low frequency bending motion. In this device, the output of the piezoelectric element is fed directly to an integral microelectronic package which includes an input low pass filter and an impedance converter. The low impedance output signal is then transmitted through the solder terminals and small gage hook-up wire to subsequent processing or recording equipment.

This accelerometer provides the following performance:

Output Sensitivity	0.05 mV/g
Output Impedance	< 100 Ohms
Dynamic Range	100,000 g
Zeroshift	Less than 0.1%
Resonant Frequency	270 kHz
Low-Pass Input Filter	Two-Pole
Electrical Configuration	Case Isolated

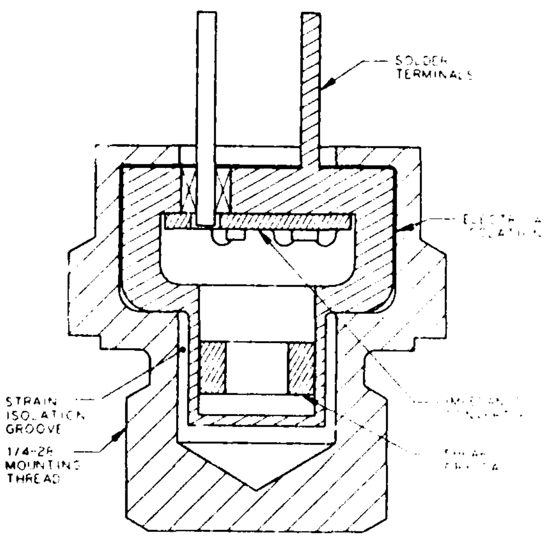

FIGURE 10
OPTIMAL SHOCK ACCELEROMETER

SUMMARY

Causes of zeroshift in piezoelectric accelerometers are:

- Overstress of sensing elements
- Physical movement of sensor parts
- Cable noise
- Base strain induced errors
- Inadequate low frequency response
- Overload of signal conditioner

Guidelines to minimize the occurrence of zeroshift errors are:

TRANSDUCER DESIGN - Use high coercivity material in bonded shear design with minimum mass loading.

SIGNAL TRANSMISSION - Use low impedance accelerometers.

BASE STRAIN - Use no-preload shear design with low base strain sensitivity.

FREQUENCY RESPONSE - Provide sufficient time constant in the electronics for long duration pulses.

OVERLOAD - Use input low pass filter, include safety factor when estimating maximum acceleration level.

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